(2)

Technical Document 2071
April 1991

Tailoring Shipboard Environmental Specifications

A Guide for Navy Program Managers

R. H. Chalmers

NAVAL OCEAN SYSTEMS CENTER
San Diego, California 92152-5000

J. D. FONTANA, CAPT, USN
Commander

R. T. SHEARER, Acting
Technical Director

ADMINISTRATIVE INFORMATION

This work was performed for the Office of Naval Technology, Arlington, VA 22217, under program element 0602234N, accession number DN 306 243.

Released under authority of
R. E. Miller, Head
Support Engineering Division

LH

CONTENTS

FIGURES

FIGURES—continued

TABLES

AUTHOR BIOGRAPHICAL DATA

NAME Chalmers, Richard H.

POSITION Head, Environmental Test Technology Office, NOSC Code 9502 (retired).

EDUCATION BSME, California State University, San Luis Obispo, 1959, with 30 units of post-graduate work in vibrations, thermodynamics, and mathematics at San Diego State University, 1962–1966.

EXPERIENCE Employed at NOSC in August 1959 (then known as the U. S. Navy Electronics Laboratory [NEL]) in the Mechanical Evaluation Branch. Worked at ever increasing levels of responsibility. Became supervisor of the Branch in March 1976. Held that position until formation of the Environmental Test Technology Office in July 1985. Served as head of that Office until retirement from the Civil Service in November 1990. Member of the Institute of Environmental Sciences since 1966, American Society of Mechanical Engineers since 1970, and of the Society of Automotive Engineers since 1981.

PUBLICATIONS

Formal Technical Reports

a) "Technical Evaluation of Army Countermeasures Receiving Set AN/TLR-7," NEL TR 931, 2 Oct 1959 (co-author, L. A. Fitzek).

b) "Engineering Evaluation of Radio Frequency Amplifier AM-1365/URT," NEL TR 970, 26 April 1960 (co-author, R. E. Hopper).

c) "Engineering Evaluation of the AN/BLQ-2 (XN-1) Sonar Beacon," NEL TR 987, 31 Aug 1960 (co-author, L. A. Fitzek).

d) "Evaluation of a 35-Foot Fiberglass Whip Antenna," NEL TR 991, 23 Sept 1960 (co-author, L. G. Robbins).

e) "Developmental Shock Test of the Panoramic Field Intensity Equipment AN/URM-126 (XN-1)," NEL TR 1015, 29 Nov 1960 (sole author).

f) "Engineering Evaluation of Radio Calibrator Set AN/URM-114," NEL TR 1028, 2 Jan 1961 (co-author, R. E. Hopper).

g) "Environmental Studies Aboard U.S. Navy Vessels in the South China and Caribbean Seas," NELC TR 1577, 16 Aug 1968 (co-author, D. L. Peterson).

h) "Modal Velocity as a Criterion of Shock Severity," NELC TR 1682, 19 Jan 1970 (co-author, H. A. Gaberson of NCEL, Port Hueneme). Also presented at the Shock and Vibration Symposium and published in Shock and Vibration Bulletin No. 40.

i) "Environmental Profiles for Reliability Testing," NOSC TR 558, 15 June 1980 (sole author).

Magazines and Technical Journals

a) "Environmental Conditions for Shipboard Hardware," Journal of The Environmental Sciences, 24:5 (Sep/Oct), pp. 13–22 (extracted from NOSC TR 558 above)

b) "Climatic testing: can we be more effective?" an article published in the December/January 1990 issue of Test Engineering & Management.

c) "Fluid Immersion: Experimental ESS Technique" an article published in the December/January 1990 issue of Test Engineering & Management.

Technical Papers

a) "Flexure Stabilization of a Reaction Vibration Machine," Shock and Vibration Bulletin No. 33, March 1964.

b) "Modal Velocity as a Criterion of Shock Severity," Shock and Vibration Bulletin No. 40, January 1970. Also published as an NELC Technical Report (TR 1682).

c) "Bolt Torque and Vibration Resistance," Proceedings of the Institute of Environmental Sciences, May 1984.

d) "Using Tuned Fixtures to Tailor MIL-S-901C," Shock and Vibration Bulletin No. 59, May 1989.

e) "MIL-S-901C Tailored for the Masthead," Shock and Vibration Bulletin No. 60, April 1990.

PATENTS "Fixtureless Environmental Stress Screening Apparatus," application for letters patent made in November 1989, Navy Case No. 71672.

INTRODUCTION

PURPOSE

This document describes shipboard environmental conditions and environmental requirements to assist computer system acquisition managers in tailoring environmental specifications effectively in their procurement documents. Environmental conditions considered in this document include natural and induced levels of vibration, temperature, humidity, and shock. The environmental levels described are based on location of the installation site on the ship and on the degree of mission criticality associated with the equipment being procured. The philosophy and empirical data underlying the environmental levels required by military specifications are discussed, allowing acquisition managers to select lower environmental levels should they choose to assume the additional risk. Tailored testing methods and mechanical design approaches and trade-offs for modifying fragile equipment to protect it from harsh environments are also addressed.

PAST EFFORTS

In the mid-1970s, the Naval Electronics Laboratory Center (NELC) conducted the Telecommunications Equipment Low Cost Acquisition Method (TELCAM) program to explore means of getting non-MIL-SPEC equipment on board Navy ships for non-mission-critical applications. Assuming only non-mission-critical applications were of interest, the results of that program would only need be updated to reflect the differences in today's ship construction methods and to compartmentalize specifications.

Earlier U. S. Navy Electronics Laboratory (NEL) programs collected shipboard environmental data to determine what changes were needed in the environmental standards of that time. Those data, when corrected for differences in ship construction, provided considerable information for this document. The information can be applied as appropriate to all degrees of mission criticality.

In the intervening years, the author worked with the Navy Printing Office to make minimum modifications to various commercial electrostatic copiers and qualify them for shipboard use. These items were purchased under reduced environmental specifications with the understanding that they could be allowed to fail without seriously compromising the mission of the ship.

Earlier environmental definition efforts were directed to areas on Navy ships where electronic equipment might be installed or where spare parts might be stored. Past and recent efforts at tailoring environmental requirements have tended to assume, erroneously, that computer equipment would be installed in only the most benign of such areas. Actually, installation sites for today's computer systems range more widely about the ship than ever, due to the compactness of the equipment, the breadth of its utility, and the relatively low cost of off-the-shelf and ruggedized equipment. Storekeepers are now using database programs on microcomputers, word processors are found wherever typewriters used to be located, and computers are now found even in engine control spaces. Clearly, it cannot be safely assumed that a typical installation site is a classical combat information center computer-room environment.

TAILORING APPROACH OF THIS DOCUMENT

Lessons learned from earlier tailoring approaches have demonstrated that the keys to effective tailoring are based on (1) understanding environmental conditions and requirements, (2) accurate identification of the range of actual installation sites for a specific equipment, and (3) definitive assessment of the criticality of its applications. With this information, an acquisition manager can make an informed assessment of the risks and benefits of specific reductions in environmental requirements. To provide this information, existing data were evaluated and extrapolated for its applicability to present and future Navy ships. Areas where data are sparse or missing are highlighted. A few revolutionary new types of platforms, such as surface effect ships, have come into existence since earlier data were collected. These new types of platforms cannot be covered accurately by the data available. However, the available published data are generally adequate to directly define the environmental characteristics of the great majority of present day and planned Navy combatant and combat support ships.

Much directly applicable vibration data are readily available. Many measurement programs have been undertaken to ensure that vibration levels used in design and qualification of new systems are not exceeded in the actual working installation. For example, vibration measurements were made in the After VLS Compartment of the USS *Mobile Bay* (CG 53), which was one of the first Vertical Launch System (VLS) equipped ships, to determine levels to be used in qualification testing of the Vertical Launch ASROC (VLA). Many reports on similar activities provided data for the vibration section of this document. Although some of these data may be old, they are still directly applicable (with appropriate scaling when necessary) to modern ships with turbine-screw drive, since the screw drive is the primary source of ship vibration.

Shipboard temperature and humidity environments depend to a large extent on the conditions ambient to the ship. MIL-STD-210C provides good data on what can be encountered, even providing statistics so the risk in selecting a certain level can be assessed. In addition, the Navy measures temperature and humidity conditions in many places about the world and maintains a computerized database that can be used to validate the requirements of Navy specifications. For example, in 1967 the computer database was accessed for a particular Marsden Square in the South China Seas to determine if MIL-E-16400 temperature requirements covered the conditions. NEL personnel visited ships operating in the South China Sea and measured intake and exhaust air temperatures. Using these measurements, transfer functions were calculated to allow predictions of the interior temperatures of ships operating in the worst-case high-temperature ambient environments.

Similar action could be taken for compartments that serve as installation sites for specific computer equipments. Due to the increased power density of modern electronics and the increased dependence on air conditioning, it is advisable to visit operating ships in worst-case operational areas and gather updated transfer function information. Unless the computer system is sufficiently non-mission-essential so it can be shut down whenever air conditioning fails, these data would have to be gathered both with and without operational air conditioning. This capability would provide the program manager with adequate information for a realistic risk assessment.

Shock data are also readily available. Navy policy requires a shock trial of each new class of combatant ships entering the Fleet. This document draws upon the author's experience with the ship shock instrumentation team from the David Taylor Research Center, Underwater Explosions Research Division. On recent shock trials with the team, the author managed the installation and operation of the shock instrumentation on the USS *Kauffman* (FFG 59) shock trials.

Direct involvement with shock measurement during ship shock trials brings about an understanding of the interaction of the ship structure and the moving shock wavefront. To successfully set the scales on the shock recorders, it is necessary to estimate the magnitude of the accelerations that will occur. Knowing the planned severity of the shocks makes estimating easy after the first shock has been recorded. But only those who have developed skill in assessing local ships structural resonance succeed in estimating levels for the first shock in the series. Along with the estimating capability comes an improved appreciation for the damage that can be caused locally; it also reveals misconceptions common in laboratory shock testing. For example, the use of a stiff fixture in attaching equipment to a shock test machine does not provide a conservative shock evaluation of the equipment. Presuming the equipment in service will be mounted in a location having a resonant frequency lower than the test fixture frequency (for example, about one-quarter of the test fixture frequency), the laboratory test is both an undertest and an overtest at the same time. Knowing this, it is possible to describe the shock environments for computer systems more accurately, and at the same time, limit the higher frequency and higher G-level parts of the shock.

The remainder of this document provides program managers with detailed data on the empirical basis for determining shipboard vibration, temperature, humidity, and shock requirements. The explanation and guidance required to use this data effectively is provided as an aid in tailoring environmental requirements to particular systems and installation sites.

VIBRATION

SOURCES OF VIBRATION

Vibration on Navy ships is ever-present. Amplitudes are small at times, such as when a ship is drydocked or is at pierside and taking its electrical power from shore sources.

As long as a crew is assigned and living and working on board, electrical power must be routed throughout the ship. Transformers are used all about the ship to convert electrical power from the high voltage at which it is transmitted to the lower voltage at which it is consumed. The hum that can be heard in the proximity of these transformers arises from mechanical vibrations of the laminations of the magnetic core material. In addition to creating an audible hum, mechanical vibrations of the magnetic core are coupled directly into the bulkheads and decks around the transformers. These mechanical vibrations in the ship's structure are at a level that can be measured for several feet around the transformers.

Fans, pumps, and compressors are constantly needed on ships for ventilation, air chilling, sanitary flushing, fire fighting, hydraulic pressurization, and many other purposes. To a large extent, these devices are driven by electrical motors that range in size from minuscule to motors that consume hundreds of kilowatts. All motors and their rotary loads are less than perfectly balanced, and they generate oscillatory forces that cause vibrations, not only in the machines themselves, but in the nearby structure of the ship. Even the air-borne sound created by these devices impinges on the nearby structure of the ship and causes a vibratory response of the decks and bulkheads. These vibrations also radiate out from their source machinery and become part of the environment affecting equipment installed in the vicinity.

Vibration levels increase when the ship separates from shore utilities because the ship's electrical power generators must be put into operation as must other pressurizing and pumping devices that provide utilities formerly taken from the shore. Vibration levels throughout the ship vary roughly in direct relationship to the amount of machinery in operation. When the ship is underway, and the main propulsion machinery is in operation, the potential for high vibration levels is at its greatest because of the enormous power level inherent in propelling a ship.

When the ship is underway, the amount of machinery in operation will vary according to the ship type and its mission. Combat operations will not necessarily cause a maximum amount of the ship's machinery to be placed in operation. For example, a destroyer searching for submarines must operate quietly if it is to detect submarines, and submarines must operate quietly to avoid detection. In addition to the amount of operating machinery on a ship, the frequency content and the point of generation of the vibrations have much to do with the vibration level that exists at a particular shipboard location. Finally, operation of the ship at high speeds or in rough seas creates the highest vibration levels. This is because propulsive forces are greatest at high speeds and because of the slamming and uneven screw loading when in rough seas.

EFFECT OF VIBRATION ON SHIP'S CREW

The sensitivity of the crew places a natural limit on vibration levels. Speeds or maneuvers of the ship that create vibration levels beyond the comfort level of the crew are normally avoided. Machines creating heavy vibrations or noise are operated only when essential. Repairs are completed as soon as possible to bring the vibration levels down to tolerable levels. Since the crew lives on the ship, vibration levels allowed are considerably lower than is the case for aircraft or tank crews where exposure times are generally much shorter.

Figures 1 through 5, taken from reference 1, and based on ISO Standard 2631, clarify knowledge about the crew's preference regarding vibrations. These figures display the lengths of time humans can tolerate vibrations at various directions, levels, and frequencies, without decreased proficiency. Notice that the human body is very sensitive to vibrations having frequencies between 1 and 8 Hz. For levels as low as 0.1 G, exposures should be limited to less than an hour. Human tolerance imposes a more stringent limitation on shipboard vibrations than do most items of installed equipment. Vibrations must be kept at low levels, or humans must be isolated, if a ship is to be an effective tool for periods of time greater than just a few hours.

Human tolerance of vibration may be the prime factor limiting vibration levels noted during vibration measurement programs. Maneuvers and speeds causing higher levels of vibration are considered harmful to the ship and its installed equipment. Such maneuvers and speeds are to be avoided unless the importance of the event mandates a risk of damage. If a ship generates excessive vibrations during normal operations, the crew undoubtedly will insist that the problem be corrected.

Vibration measurements performed on the USS *Chandler* (DD 717) display how the ship's crew sensitivity to vibrations acts to limit vibration levels. An automatic environmental data recording system was installed on the ship to document temperature, humidity, and vibration levels. The crew had been complaining of vibration levels they felt were higher than proper for continued good health of the ship. After a trip to a shipyard, in which both screws were changed, vibration was reduced to a level that the crew found acceptable. The before and after vibration levels, as recorded by the environmental data system, disclosed a substantial reduction in vibrations at 4, 11, and

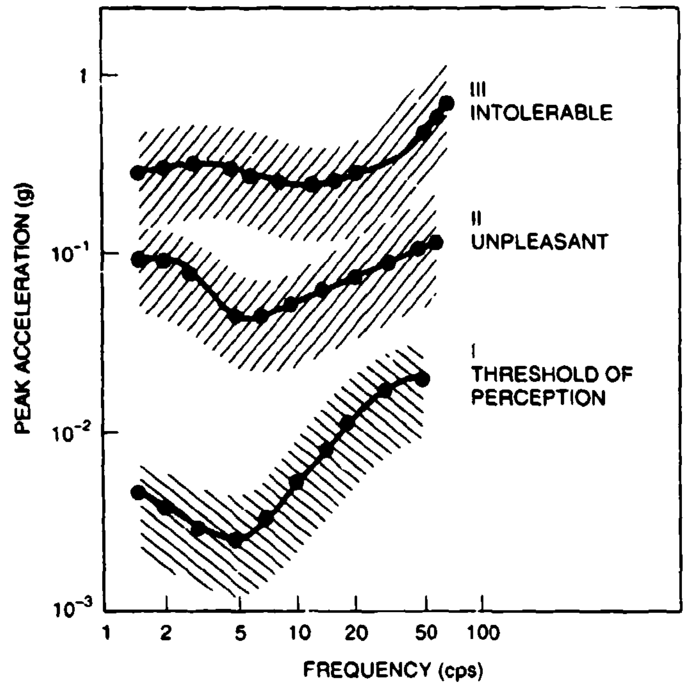

Figure 1. Average peak accelerations at various frequencies at which subjects perceive vibration.

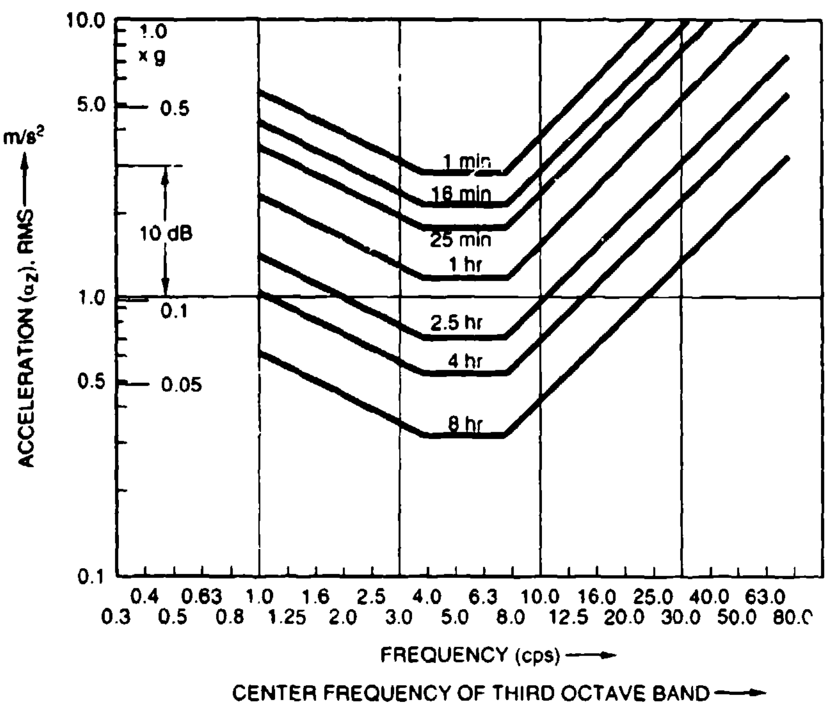

Figure 2. Vibration exposure limits as a function of frequency and exposure time.*

* (From Harris, C. M., *Shock and Vibration Handbook*, 3d ed., New York: McGraw-Hill, Inc., 1988. Reproduced with permission of the publisher.)

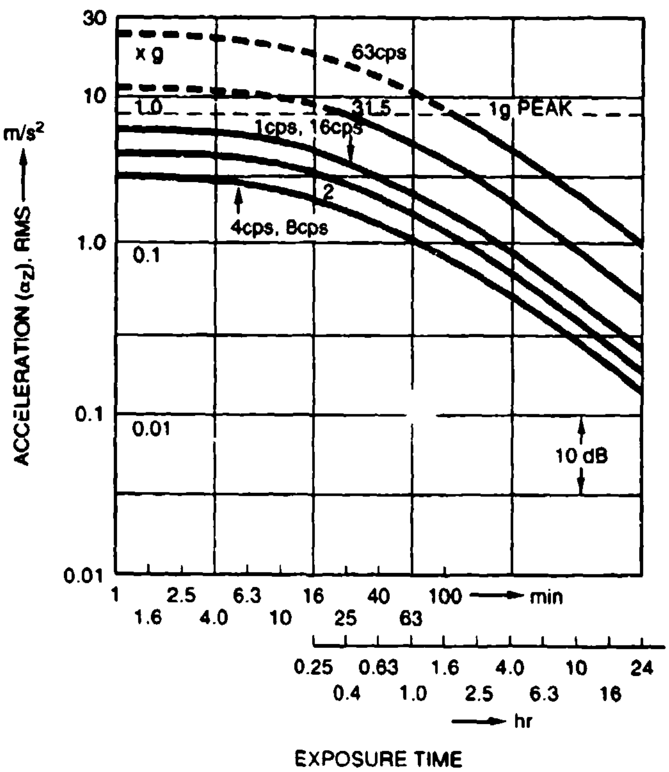

Figure 3. Longitudinal whole-body acceleration limits as function of daily exposure time: fatigue-decreased proficiency boundary.*

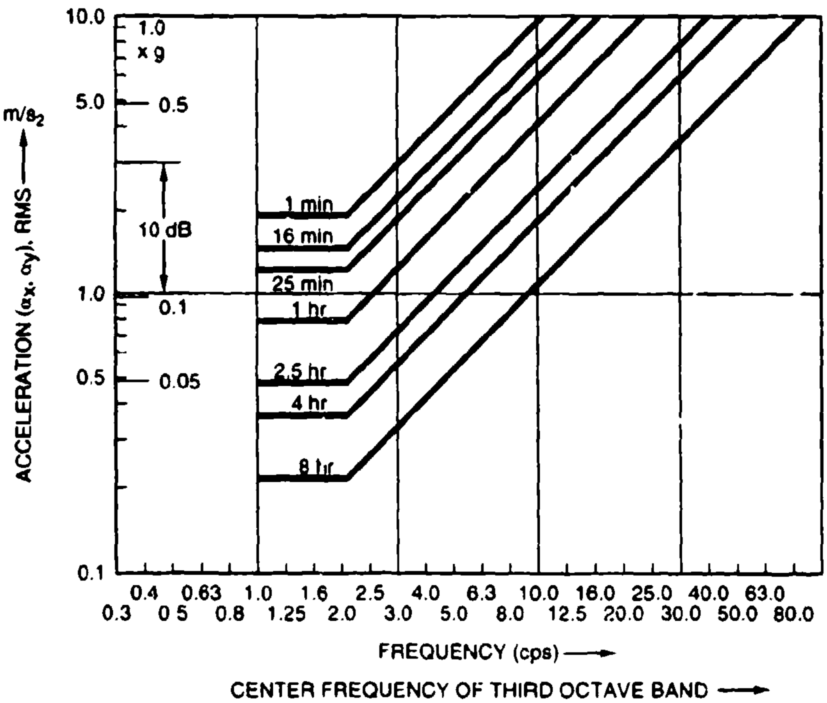

Figure 4. Transverse whole-body acceleration limits: fatigue-decreased proficiency.*

* (From Harris, C. M., *Shock and Vibration Handbook*, 3d ed., New York: McGraw-Hill, Inc., 1988. Reproduced with permission of the publisher.)

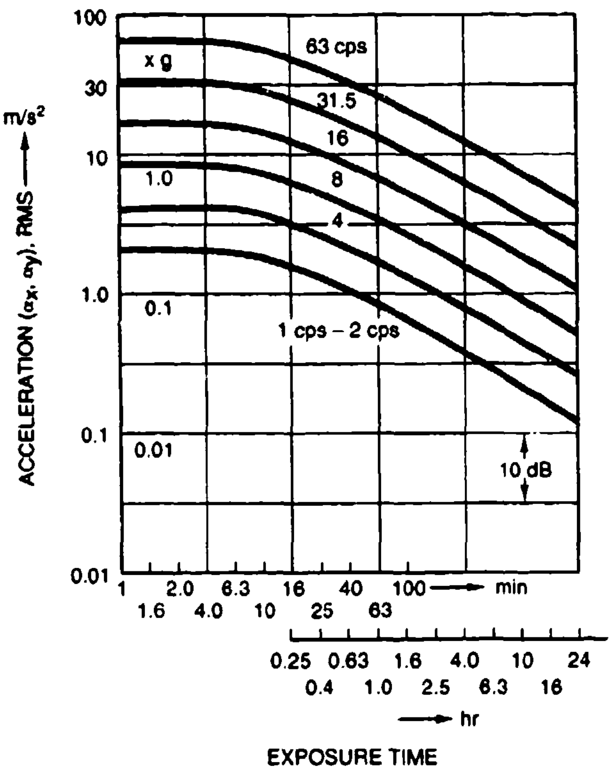

Figure 5. Transverse whole-body acceleration limits as a function of daily exposure time: fatigue-decreased proficiency boundary.*

18 Hz (see figure 6). Note that, with the exception of 60 Hz, the before and after vibrations were below the 0.1-G tolerance level. Figure 6 shows the peak vibrations measured in the combat information center (CIC) on the ship in all directions, while figure 7 displays peak levels measured on the mast. In figure 7, except 60 Hz, the 0.1-G tolerance level is exceeded at 4 Hz and 17 to 18 Hz. Changing the screws reduced the 17- to 18-Hz vibrations to well below the 0.1-G level. Although the 4-Hz vibration was still slightly above 0.1 G on the mast, it had been reduced from approximately 0.35 G to about 0.11 G. Because the mast is normally unmanned, its vibrations were small enough to no longer worry the crew.

* (From Harris, C. M., *Shock and Vibration Handbook*, 3d ed., New York: McGraw-Hill, Inc., 1988. Reproduced with permission of the publisher.)

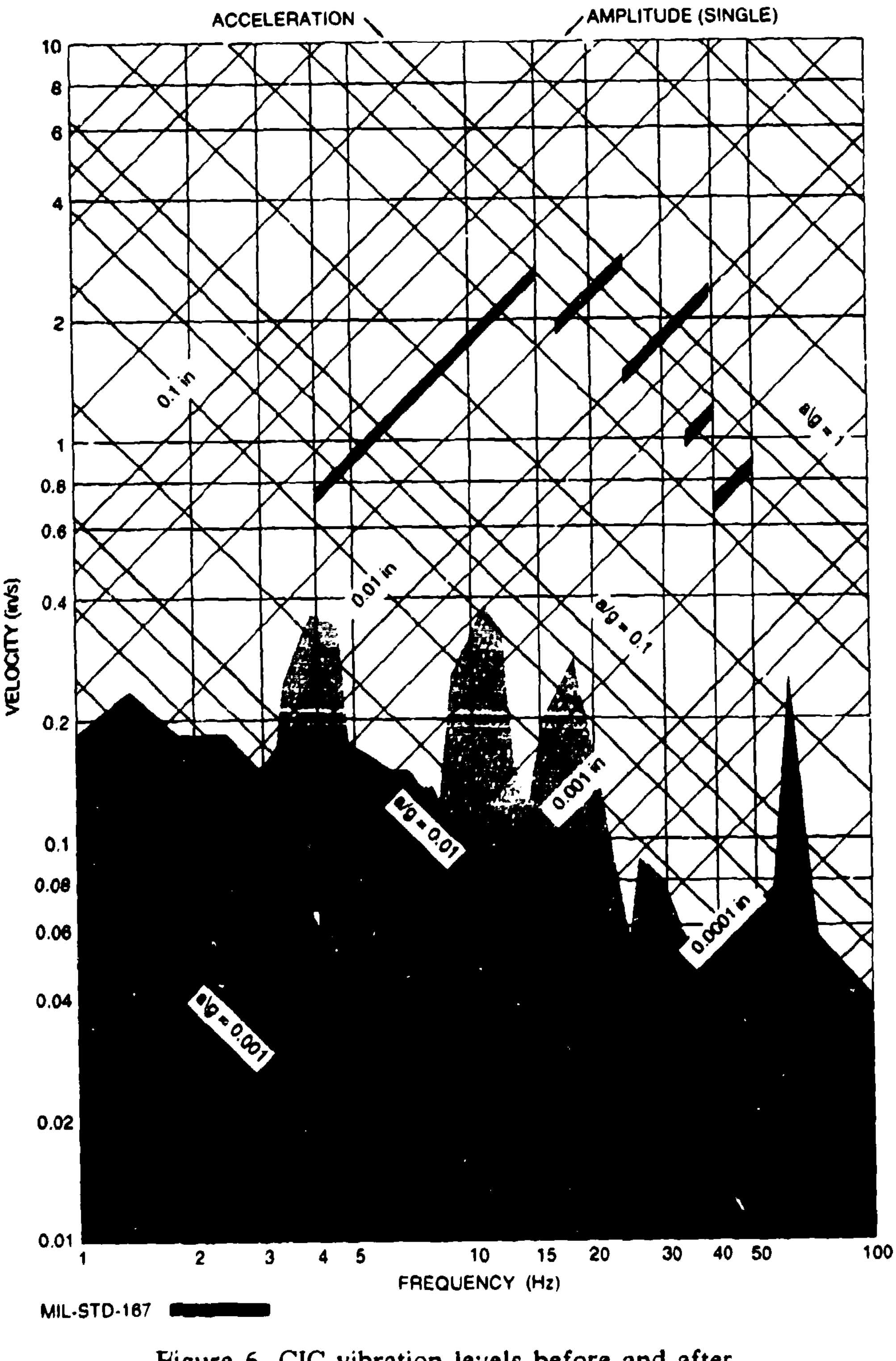

Figure 6. CIC vibration levels before and after changing screws on USS *Chandler* (DD 717).

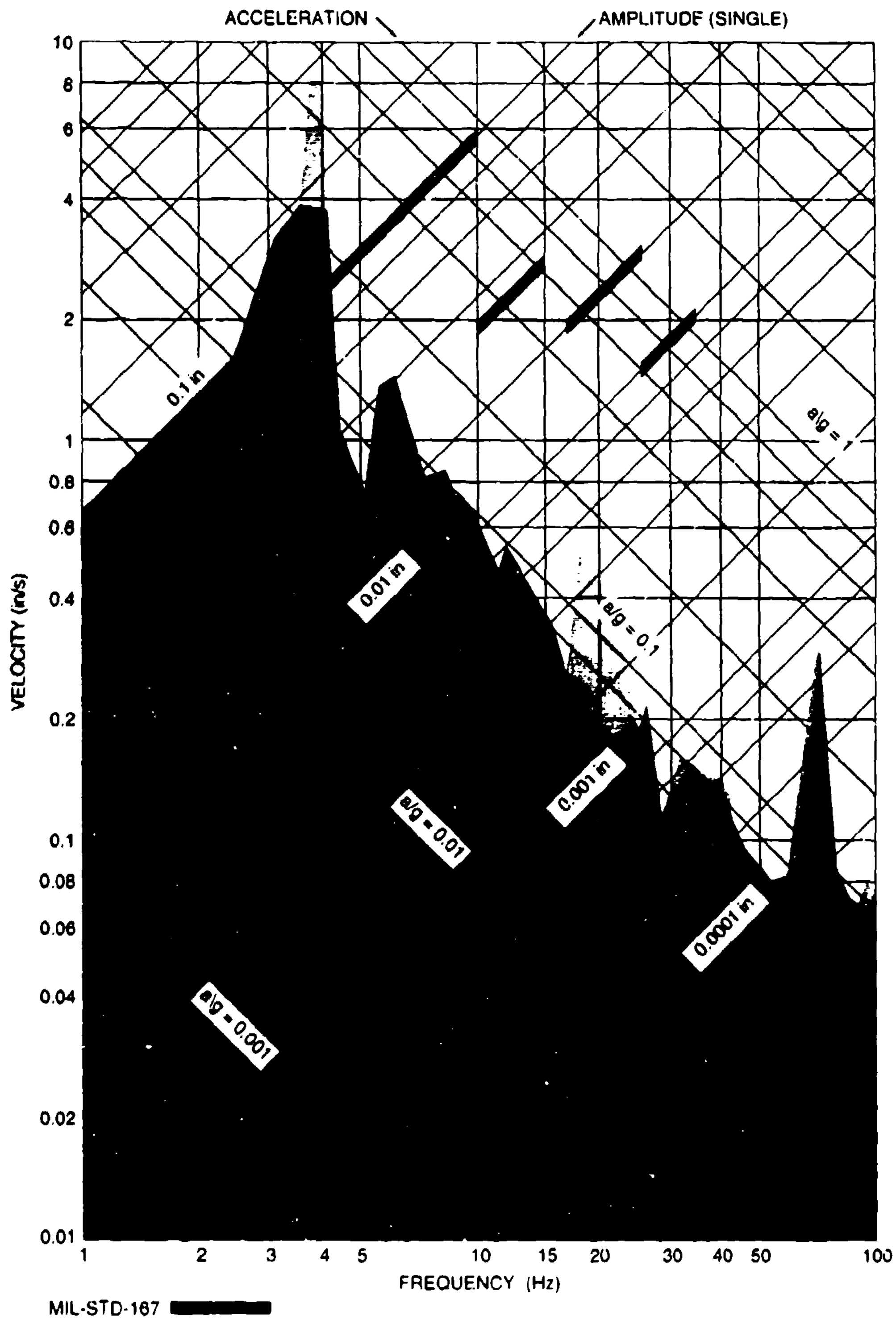

Figure 7. Radar mast vibration levels before and after changing screws on USS *Chandler* (DD 717).

EFFECT OF VIBRATION ON SHIP'S STRUCTURES

Vibration engineers like to say "All the world is a spring!" The expression is clear if one thinks about how the earth responds to earthquakes. As earth's tectonic plates attempt to move with respect to one another, stresses are built up. When the stresses reach a magnitude that the surrounding soil structure can no longer resist, sudden slippage of one surface relative to the other relaxes the stresses, and oscillatory motion of the area results. The tremors are coupled from one side of the earth to the other directly through the liquid center, and laterally through the crust. Sensitive seismometers located about the world not only inform us that an earthquake has occurred somewhere, but can pinpoint the origin and magnitude of the motion. These motions are propagated by the "springiness" of the earth.

Even though made of stiffer materials than the earth, man-made structures such as buildings, bridges, ships, and machines, respond to loadings similarly. Because man-made structures are stiffer, response frequencies are higher than those of the earth responding to an earthquake. A transient force applied to a ship at a point, for example the thrust bearing on the main propulsion shaft, is propagated through the ship just as the earth responds to an earthquake force. Energy from an exciting force is absorbed into the ship's structure as deformation of local structure and stored briefly as potential energy. It is then released into surrounding structure at rates determined by the spring characteristics of the structure. How far and at what magnitude the force is transmitted depends on the mechanical impedance or mobility of the ship's structure and, if the force is repetitive, the repetition frequency.

The shape of a ship is dictated by many considerations other than its ability to resist vibrations. The structure must be strong enough to withstand the rigors of going to sea, and the hull must be slender for minimal drag. Also, vertical stiffness must be great enough to support all the machinery and structure directly above. One of the most common ways to avoid stresses in a ship is to incorporate maximum flexibility in the design. Consequently, a ship often is stiff longitudinally but flexible when subjected to vertical and side-to-side force couples. In fact, many ships have built-in expansion joints that serve to relieve high stresses that would otherwise result from vertical and side-to-side force couples.

These natural and intended flexibilities limit the magnitude and frequency of vibrations transmitted about the ship. For example, the screws generate vibratory forces in all directions, but those acting in the longitudinal or fore and aft direction are the heaviest. Blades of the screws lose part of their bite momentarily as they pass the stern post. As these forces are transmitted forward in the ship, the vertical and side-to-side flexibility of the ship's structure dissipate the forces more readily than does the fore and aft stiffness of the structure.

EFFECT OF DISTANCE ON TRANSMISSION OF VIBRATIONS

Even though longitudinal stiffness of the ship is greater than side-to-side or vertical stiffness, the large longitudinal dimensions of many ships limit the effective stiffness. This thereby limits the magnitude and frequency of vibrations that are transmitted. Vibration engineers sometimes use a factor termed "spring constant" to indicate how a structure will behave under vibration or shock conditions. High structural spring constants lead to high natural (resonant) frequencies and provide unamplified transmission of vibration frequencies up to about 20 percent of the structural resonant frequency. Depending on the damping inherent in the structure, driving vibrations at frequencies between 20 and 140 percent of the natural frequency will be amplified by as much as 5 to 10 times the input. Above 140 percent of the natural frequency, the motion transmitted is attenuated with respect to the driving motion due to the relative flexibility of the structure.

An example of how the longitudinal natural frequency of a ship is affected by length, consider a hypothetical, single degree-of-freedom model of a ship whose longitudinal cross-sectional area allows 0.01 millimeter of motion in a length of 10 meters under a 5000-Newton force. Such a section of structure exhibits a spring constant of 500,000,000 Newtons per meter and, assuming a mass of 1876 kilograms, would exhibit a natural frequency of about 70.7 Hz. Destroyers are often 100 meters or more in length and could be represented by 10 of the above sections arranged in series. When spring constants are loaded in series, the overall result is similar to loading resistors in parallel; that is, 10 sections in series provide one tenth the spring constant. Therefore, if a 10-meter-long section exhibits a 70.7-Hz resonance, 10 of these sections arranged in series should exhibit a 22.4-Hz resonance since resonant frequency varies directly with the square root of the spring constant. Reducing the spring constant by a factor of 10 reduces the resonant frequency by the square root of 10, or 0.316 of its original value.

Aircraft carriers sometimes reach 335 meters in length. Using the same reasoning we used for the destroyer above, we would arrive at a longitudinal natural frequency of 12.2 Hz for the carrier. It should be noted that the values used here represent no specific ship or ship's structure. They were chosen only to demonstrate how length affects the magnitude and frequency content of transmitted vibratory forces. In fact, calculations indicate that a solid bar of steel 10 meters in length with the same cross-sectional area but no mass loading would resonate at approximately 400 Hz. No practical ship will have a structure that provides a resonant frequency nearly one-fifth that of solid steel. Such a ship would have essentially no usable space inside, and it undoubtedly would not provide sufficient buoyancy.

VIBRATION MEASUREMENT PROGRAM

The foregoing discussion should serve to explain how levels decrease with distance from the generation point of vibration. In most cases, where vibrations were measured on board operating ships, the highest levels were generated by the ships screws. In the few instances when data were taken near the screws, levels similar to those specified in MIL-STD-167 (reference 2) existed. On most ships, in the areas where electronic equipment would likely be located, vibration levels seldom exceeded 0.1 G peak. Only on aircraft carriers and small gunboats were levels measured that were larger. These levels, though, seldom exceeded 0.2 G.

Local Vibration Transmission

With regard to the 60-Hz vibrations shown in figures 6 through 10, it should be noted that figures 1 through 5 show that humans can tolerate 7 to 10 times the amount of vibration amplitude in bands centered at 63 Hz than they can in bands centered at 8 Hz. In addition, based on the earlier discussion describing how shipboard structure affects vibration transmission, it is clear that vibrations much above 30 Hz are generated locally. Such vibrations will not be transmitted far from the point of generation. For these reasons, vibrations above 30 Hz are not of great concern unless they occur at amplitudes considerably greater than 0.1 G.

Measurement Locations

Figures 8, 9, and 10 show the peak fore and aft, athwartship, and vertical vibrations measured on approximately 20 ships representative of the Fleet during the Vietnam operations. These levels were measured in spaces on the ships in which electronic equipment was located. Figure 11 shows vibration regions on the ship that were arbitrarily established for use in reporting the vibration data at various locations. Vibrations were recorded on operating ships on a noninterference basis, and even though considerable electronic equipment is located in the "masthead region," mounting sensors on masts would have interfered too greatly with ships operations, so "masthead region" data are sparse. Sonar equipment is often located well forward in the "main region," but distance from the screws placed low priority on obtaining vibration measurements in these areas. "Main region" data are, therefore, also sparse. Seldom was any electronic equipment installed in the "after region." Electronic spares, however, were found stored in the Steering Ram Room on the USS *Waddell* (DDG 24) directly beneath the After Steering Compartment, and just above the screws. Consequently, vibrations were recorded in the room, and they proved to be some of the higher levels of data recorded during the measurement program. But, by far, most of the measurement locations were in what is shown in figure 11 as the "above main region."

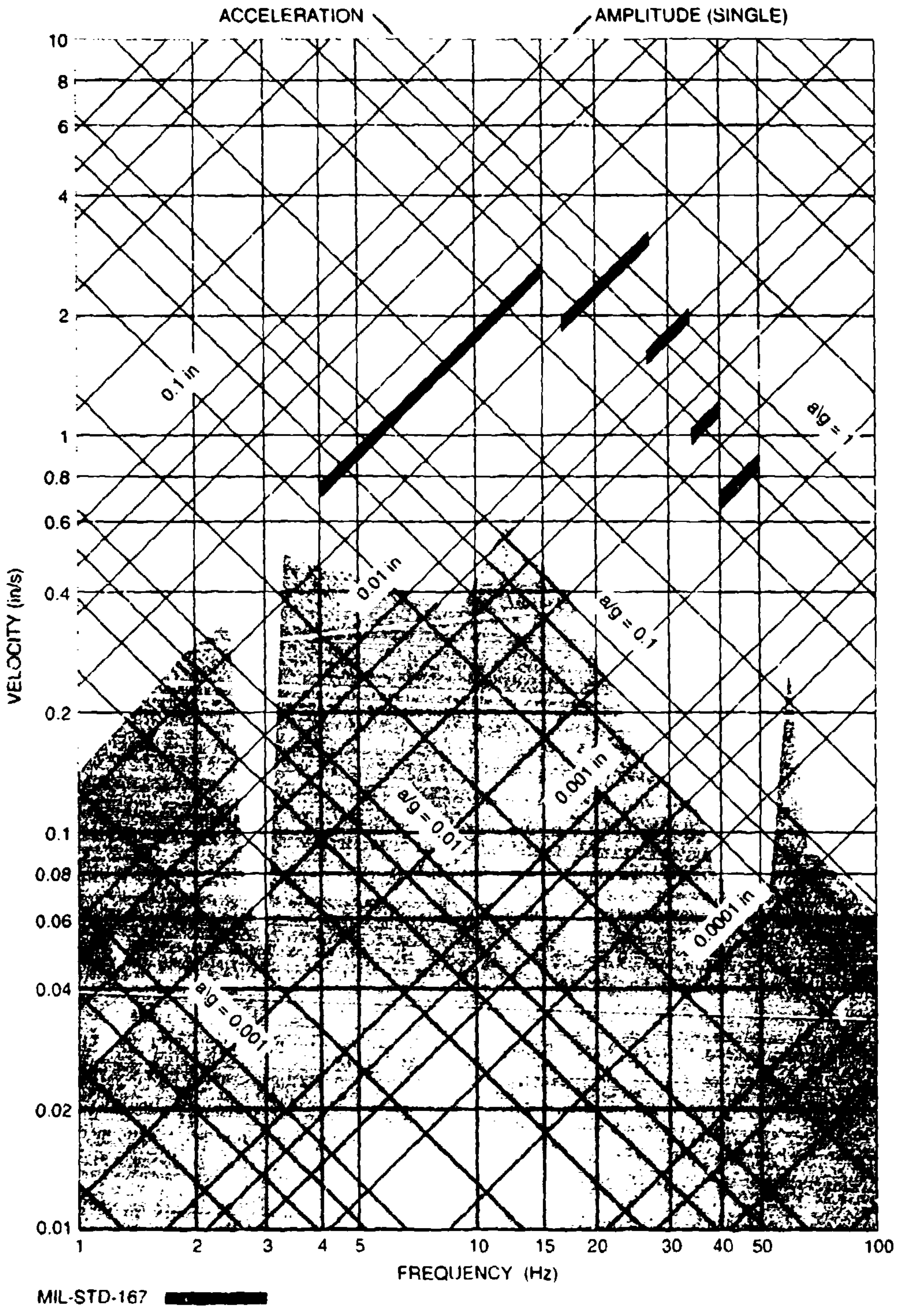

Figure 8. Fore and aft vibration levels.

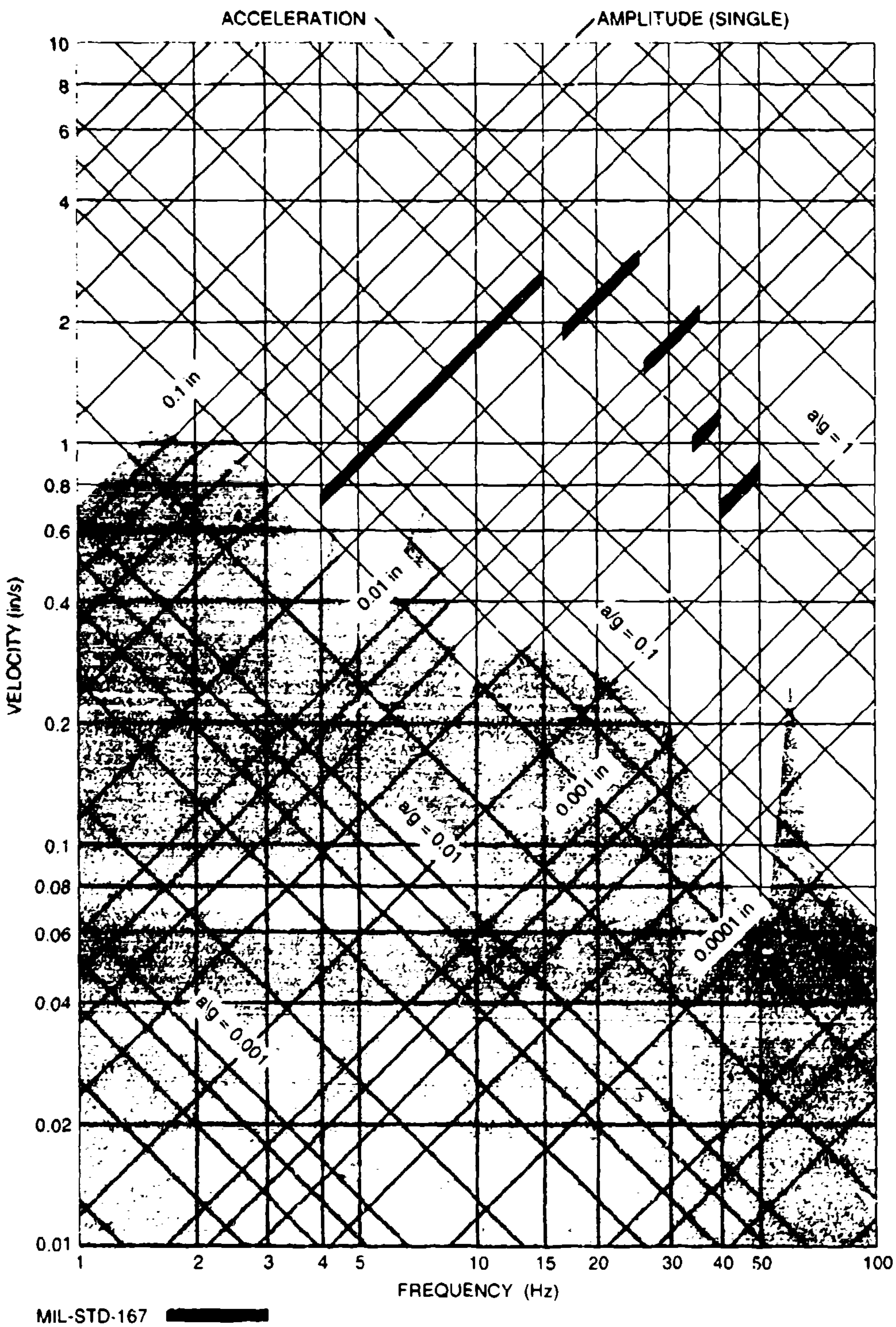

Figure 9. Athwartships vibration levels.

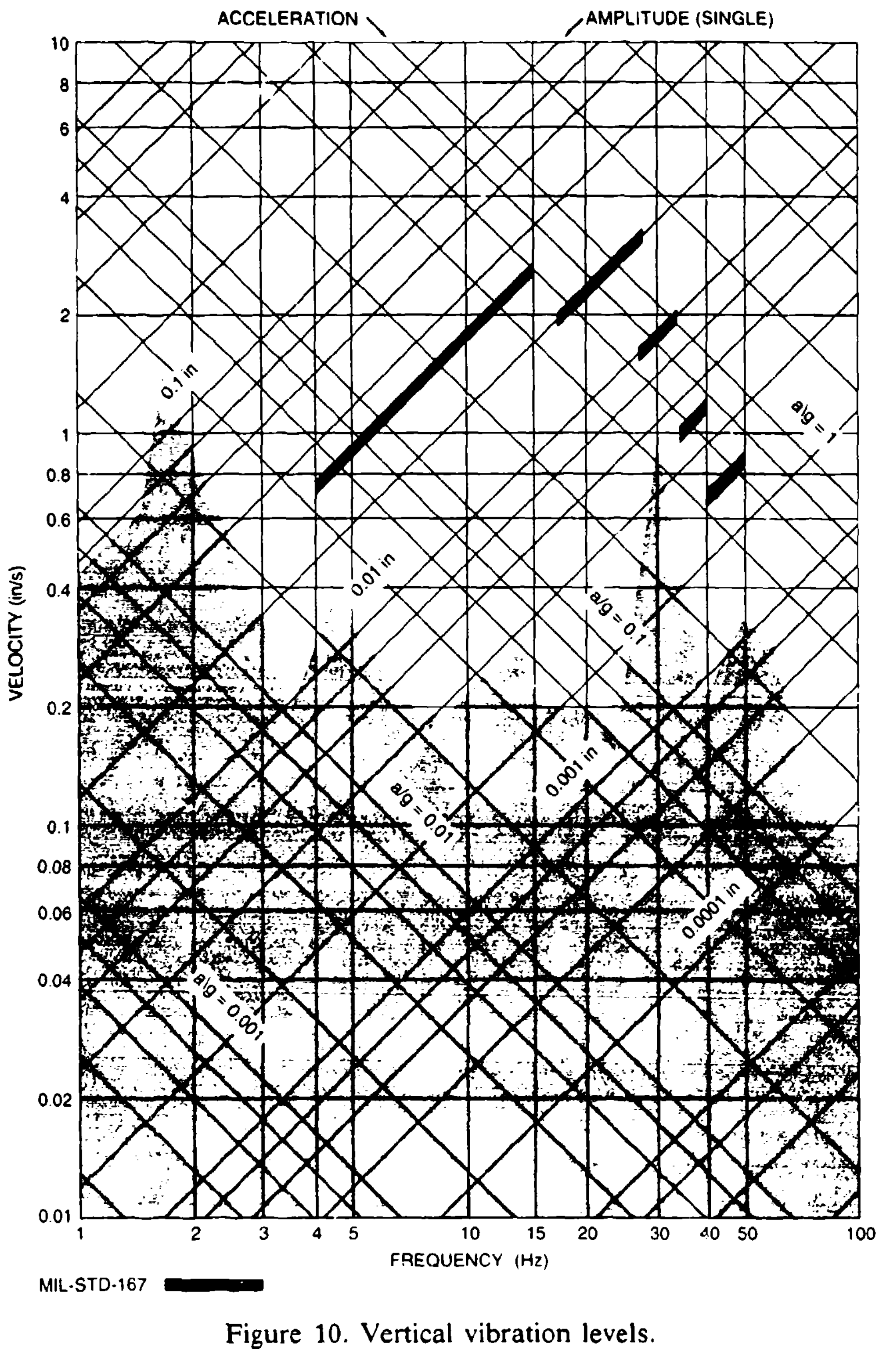

Figure 10. Vertical vibration levels.

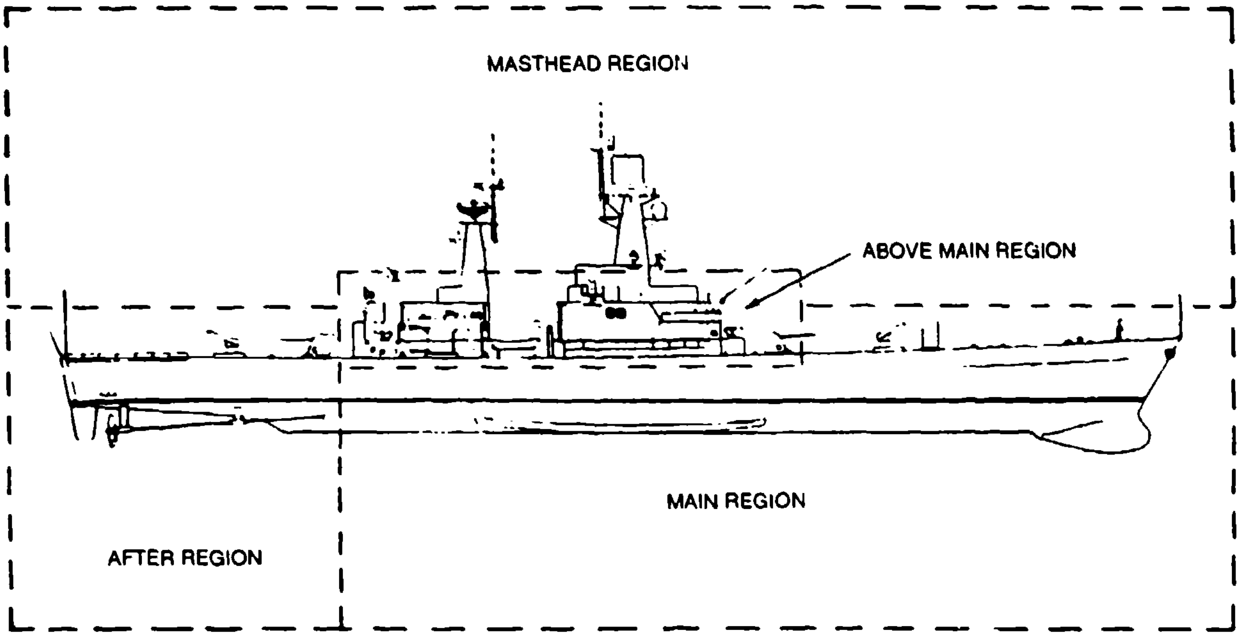

Figure 11. Ship categories and major vibration regions.

Data Recording

Most of the data points were accumulated with manually operated recording systems (see references 3 and 4), and they recorded what the operators indicated were the heavier vibrations during the period they were on the ship. Operator reaction time, though, precluded recording some of the heavier vibrations, those that might have represented wartime damage conditions. For example, the *Waddell*, cruising just off Vietnam at good speed, ran across submerged fishing nets. The nets wrapped around the *Waddell*'s shafts and screws, causing considerable unbalance. Violent vibrations were felt throughout the ship. Before the data recorder could be energized, the bridge crew stopped and reversed the shafts. This action cleared the nets from the screw and stopped the vibrations before the recording system was able to document the levels. With smooth operation restored, the *Waddell* then proceeded back to her course and speed.

Subjectively, vibrations during this event were much heavier than those used in qualifying equipment for use on Navy ships (MIL-STD-167, (reference 2)), but because the ship was not under immediate threat and was able to take immediate corrective action, the problem was resolved quickly, so quickly in fact, that tape recordings documenting the levels were not obtained. Had the destroyer been involved in resisting or conducting hostilities, it may have been necessary to maintain the best speed possible, with concomitant vibrations, for as much as several hours. All the installed equipment would have then had to endure as best it could.

Additional Data Sources

Vibration data from the measurement program were combined with data reported by many Navy sources to prepare a vibration profile for non-mission-critical shipboard telecommunications equipment. A complete listing of the data sources is given as item 19 in NOSC TD 335 (reference 5). Appropriate figures from that document are reproduced here as figures 12 through 19. Notice that even with the augmented sources of data, reported vibrations had an upper limit of 0.2 G. On ships other than carriers and gunboats, levels seldom exceeded 0.1 G. In compiling this data, all data attributed to the response of installed equipment were rejected. Only those that described the ships structural motion (e.g., the vibrations that would be input to equipment installed at that point) were retained. For instance, all data reported for the USS *Iwo Jima* (LPH 2) in NELC 1701 (reference 4) dealt with either the responses of installed medical equipment or improperly secured gas bottles in the Aerology Compartment. Since these data did not describe input vibrations that electronic equipment might normally have had to endure, they were not given consideration in figures 8, 9 and 10. Almost all the remaining reported measurements were made in locations on ships that fall within the region of figure 11 labeled the "above main" region.

Gunboat and Carrier Variations

Why are vibration levels higher on gunboats and aircraft carriers? For one thing, the gunboat is small, about 164 feet overall. It has about the same longitudinal section stiffness as do larger ships, but the vibrations generated by its screws receive less attenuation (due to distance) before reaching the "above main" region. Aircraft carriers have four shaft and screw arrangements, staggered longitudinally as is necessary to fit within the confines of the hull. This shortens the structural path for vibration transmission and adds to the probability of generating beat frequencies due to the small speed differences of the shafts. Further, aircraft carriers often move at greater speed than other surface ships in carrying on air operations. They expend considerably more power in achieving and maintaining their speed through the water and could reasonably be expected to generate larger vibrations.

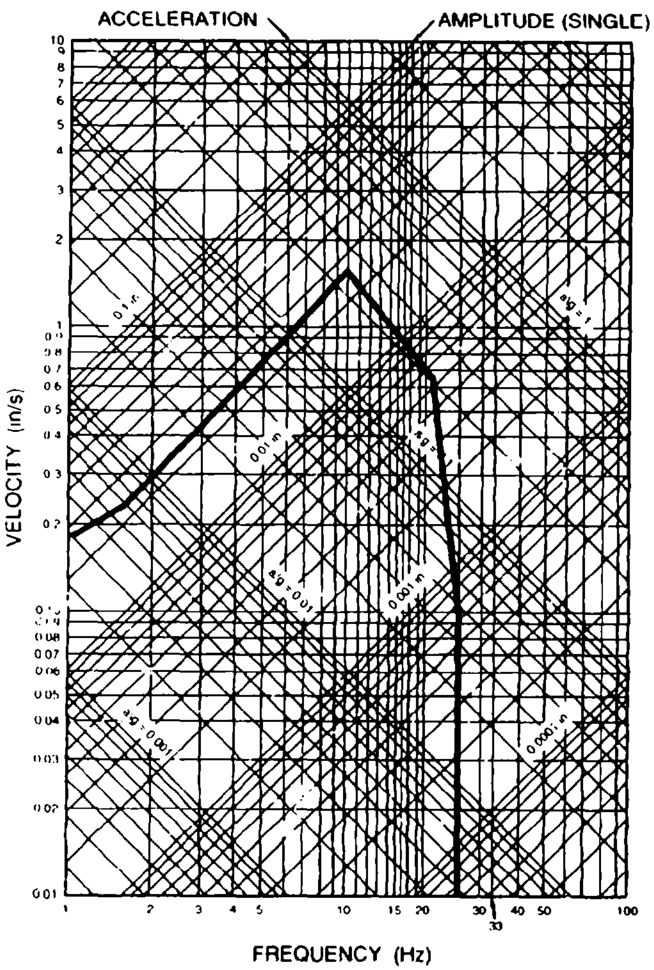

Figure 12. CVA-CVAN TELCAM vibration limits.

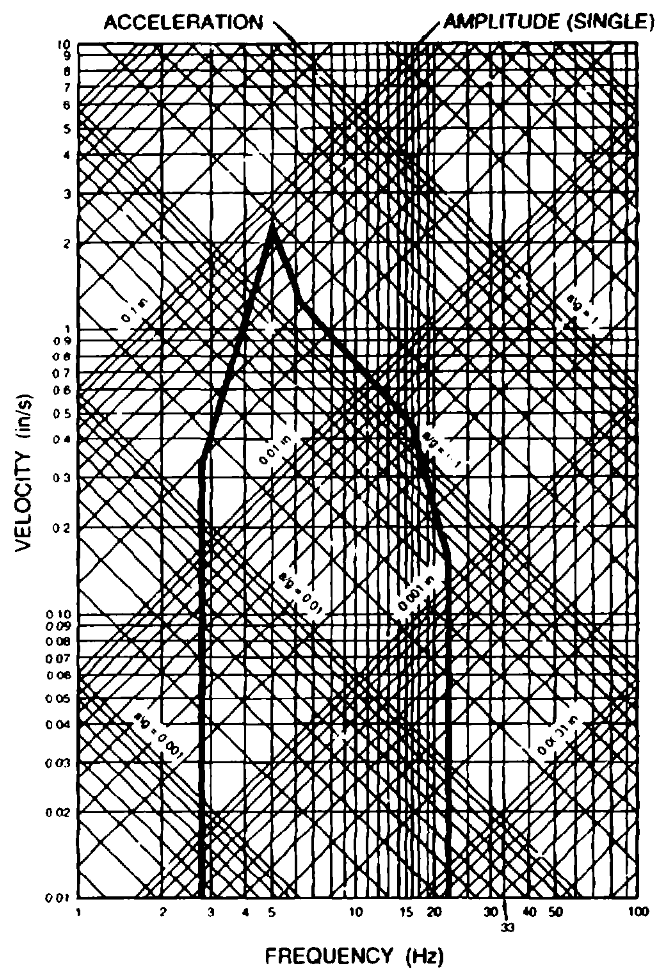

Figure 13. DDG-DD TELCAM vibration limits.

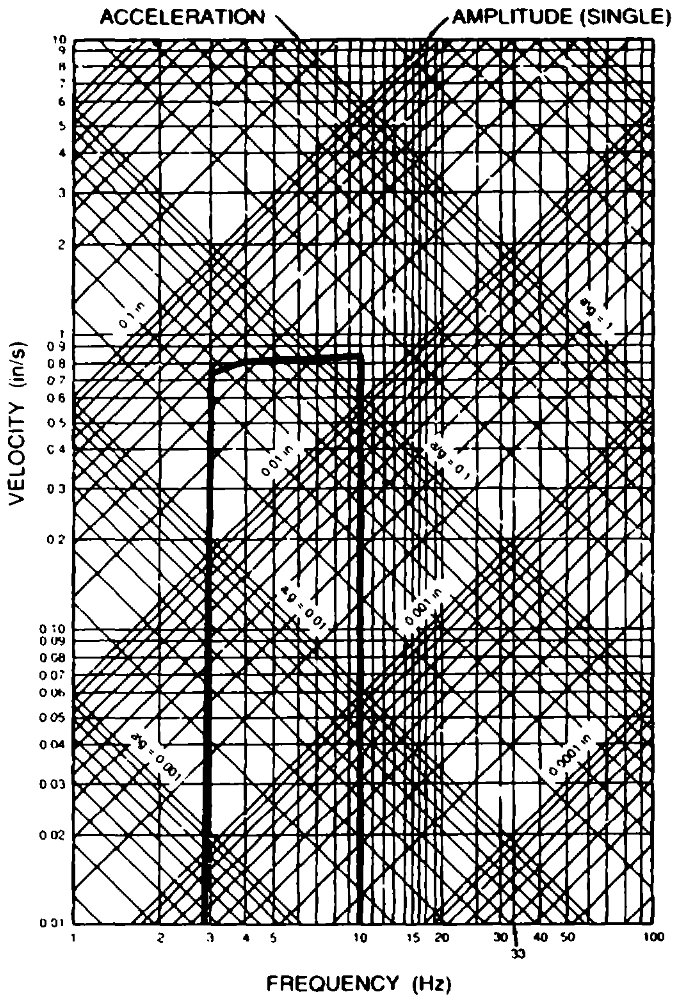

Figure 14. DEG-DE TELCAM vibration limits.

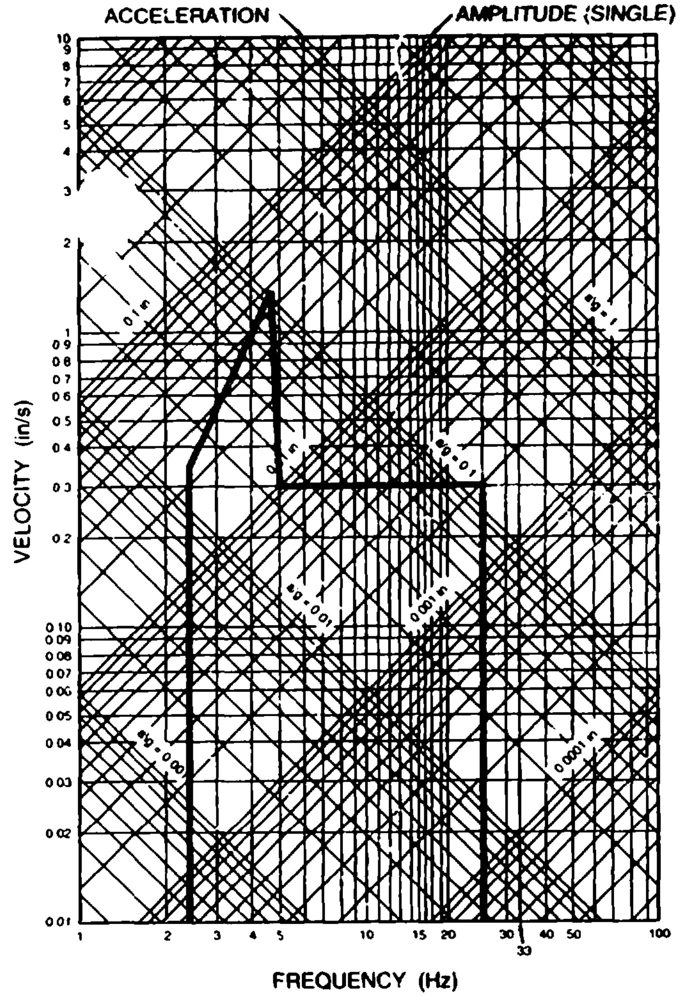

Figure 15. DLG-DLGN TELCAM vibration limits.

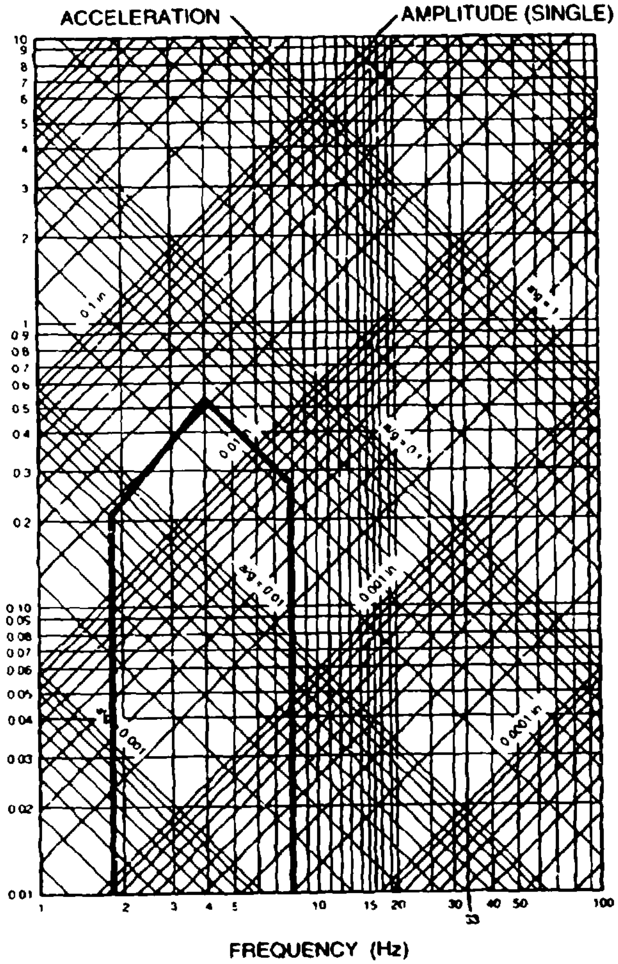

Figure 16. LPH TELCAM vibration limits.

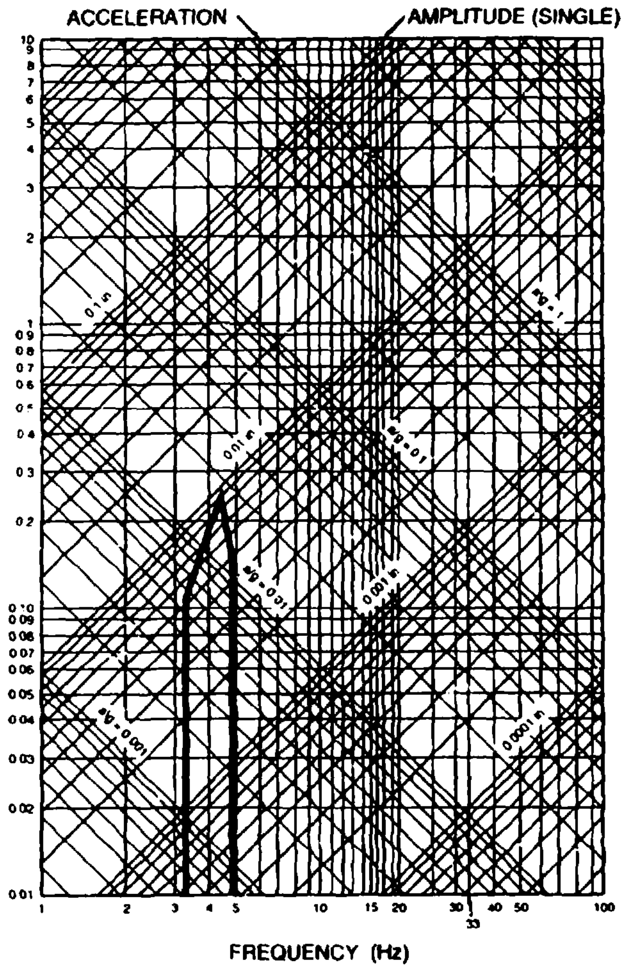

Figure 17. LST TELCAM vibration limits.

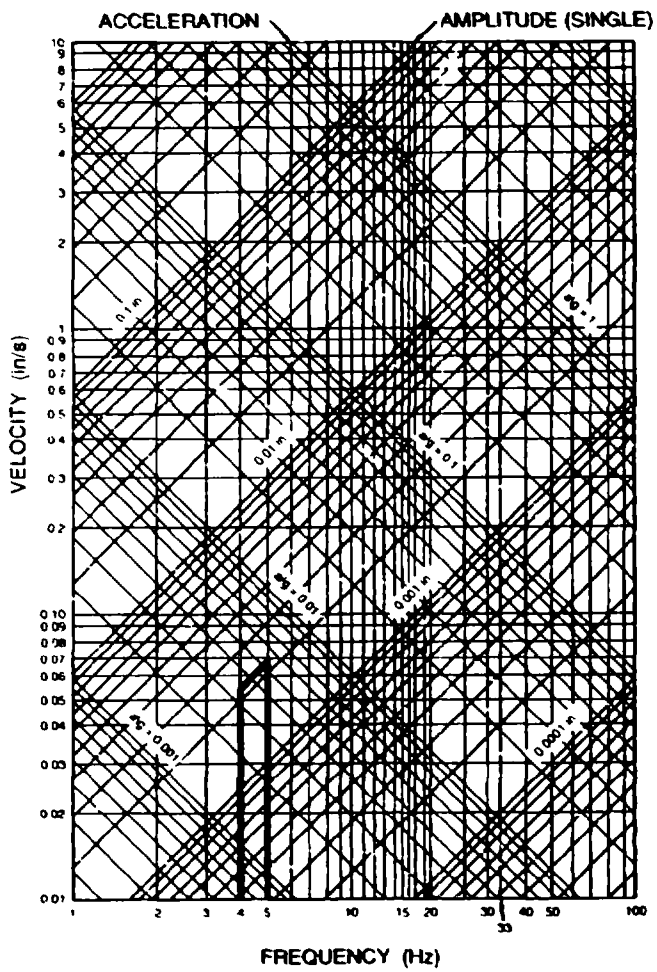

Figure 18. MSO TELCAM vibration limits.

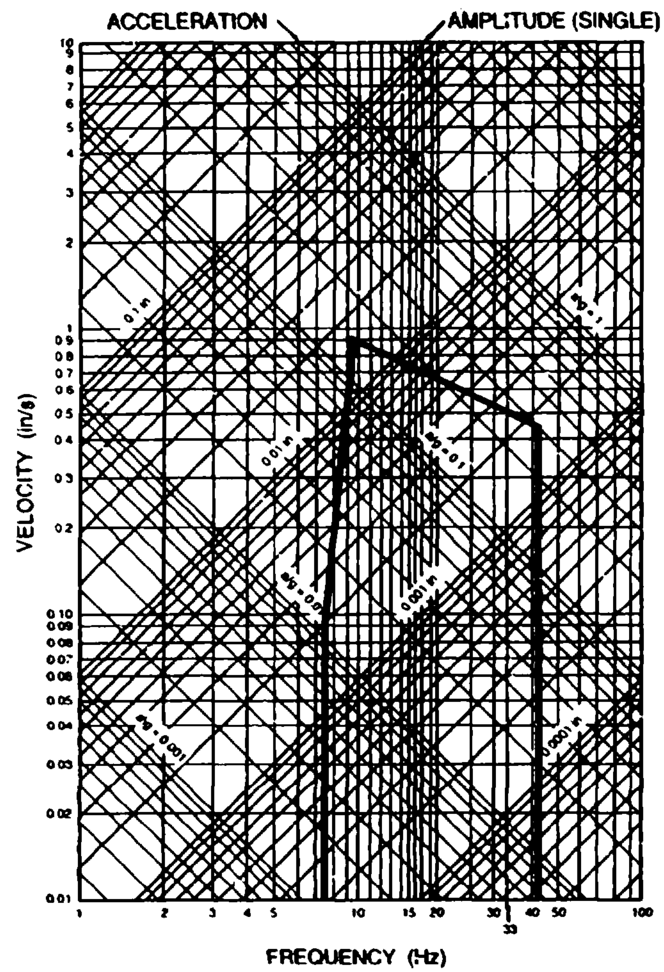

Figure 19. PG TELCAM vibration limits.

Huerlstic Vibration-Level Formulae

The normal day-by-day vibration environment on most classes of surface ships can be described in a simple mathematical relationship between peak vibration level and the distance between installation location and the screws:

$$Vp = \frac{1.7}{(D - 30)^{1/2}} \qquad (1)$$

where Vp = peak acceleration level at any frequency from 4 to 50 Hz, G

D = distance in feet from stern to the installation location

For aircraft carriers, a similar equation can be used:

$$Vp = \frac{1.5}{(D - 30)^{1/3}} \qquad (2)$$

These levels are admittedly low, amounting to roughly one-tenth to one-fifth of the usual shipboard vibration requirement as defined in MIL-STD-167 (reference 2). Any equipment of practical value installed on the ship should operate without vibration impairment at these levels. The vibration tolerance of equipment should rise in direct relationship with the criticality of the equipment to the ship's mission. MIL-STD-167 levels should be considered a generally accepted upper level. MIL-STD-167 does not necessarily describe the highest levels that will ever occur. It merely describes an arbitrary level above which the Navy accepts responsibility for operation of all installed equipment. Unique applications often require vibration tolerance greatly exceeding MIL-STD-167 levels. Examples of these are electronic control circuitry mounted directly on diesels, gas turbine generators, hydraulic power supplies, or any noise-producing machinery.

DETERMINATION OF VIBRATION REQUIREMENTS

Equipped with descriptions of the peak vibration levels, we need to address the question of how long a period of time an item should be expected to endure a given level of vibration. A well-designed piece of electronic equipment should certainly retain all capabilities for at least 10 years after installation, and with development costs of new systems what they are today, a 20-year service life is desirable. Of that 20-year service life, the ship on which the equipment is installed is underway about 50 percent of the time. That means that the equipment will experience the usual low-level vibration described above for a total of 10 years. To make certain the equipment will not be impaired or slowly degraded by long-term exposure to low-level vibration, it should be exposed to vibration testing during the process of qualifying the equipment for shipboard use. Obviously, it would be wise to have the vibration test match the service life in length so that results bear a one-to-one time correlation on what could be expected in service. Equally obvious is the fact the vibration qualification test must be somewhat shorter, even though it loses the confidence offered by a one-to-one time correlation. How can the test time be shortened without abrogating validity of the results?

Equivalent Techniques

Fackler (reference 6) defines a good vibration test as one that fails equipment destined to fail in service and will not fail equipment that is satisfactory for service. He further states that this definition was found to be deceptively simple:

> Several weaknesses exist in our ability to perform a good test. Most are unavoidable. However, it is necessary to discuss them so that they may be avoided to the largest extent possible. The primary weaknesses result from a lack of adequate field data, the use of motion-control test practices which ignore the interaction between equipment and structure, attempts to write general specifications, and approaches used to accelerate time.

Thus, our approach is technically weak in that we lack adequate data and cannot properly account for the interaction between equipment and structure. But, in a general way, we can describe the vibration environment on surface ships, and we can feel confident that only great changes in propulsion methods or in vibration tolerance of the crew members are likely to change our description appreciably. That leaves, then, only the "approaches to accelerate time" with which to deal.

Approaches to Accelerate Time

Fackler (reference 6) discusses several of the methods currently used to affect compression of the vibration test to the service life ratio. One way to abbreviate vibration test time is to look at possible modes of failure and then aggravate the aspects of vibration testing that tend to reveal those modes. One category of vibration failure exhibited by many equipments is that of mechanical fatigue, either by breakage or general loosening of major structural elements or nonstructural components such as switch contacts or component lead wires. These failures are characterized by the fact that the failure remains after the vibration stimulus is removed. A second category of failure is one in which the failure disappears when the vibration stimulus is removed, or sometimes, when it is reduced. Failures of this second category are not caused by overstressed conditions, but by insufficient stiffness or clearance in the design of the item under test. Both failure categories are sensitive to the amplitude of the vibration stimulus, though they differ in that failures of the second category may never occur at reduced vibration levels, while failures of the first category merely take longer to appear.

To explore the possibility of shortening test time for disclosing weaknesses related to fatigue failures, we can use the results of work done to determine how well aluminum and steel endure reversed bending. From published endurance data, we can easily determine what amplitude of reversed bending stress is necessary to cause failure to occur at 10,000 cycles rather than 500,000 (45,000 rather than 33,000 psi for mild steel). Presuming fatigue failures in vibration are due mostly to reversed bending stress, we have a method of shortening time available to us. We can raise the input amplitude to the point where the item under test will receive in 2 hours the same fatigue it would receive at lower vibration levels in 10 years on the ship. A vibration test time and an amplitude can be specified that will bear a known relationship to the service environment, and will, thereby, provide a known time compression. This is essentially what MIL-STD-167 intends to accomplish in its endurance tests.

Hastening failures of the second category cannot be handled as directly as fatigue failures. Amplitude-sensitive failures indicate improper design, and though they may tend to occur at ever lower vibration amplitudes as fatigue is accumulated, they do not bear a direct relationship to fatigue. Normally, it is considered satisfactory to simply apply for a short time a somewhat higher input amplitude, ranging from 2 to 10 times greater than is expected in the field, while watching for any undue response from the item under test. The Variable Frequency Tests of MIL-STD-167 are directed toward disclosing these types of failures.

RANDOM VIBRATION

Discussions of vibration thus far have been mostly in terms of sinusoidal, single-frequency operations, both in describing the shipboard environment and the tests used to qualify equipment for shipboard use. Now that random vibration measurement equipment and techniques have become available, and vibration testing equipment can generate controlled random vibrations, it is considered proper to specify and apply random vibrations whenever possible. All vibration environments, even those we attempt to make pure single-frequency environments, actually contain recognizable amounts of energy at many frequencies. Some failures, particularly those that go away when vibration is stopped, result from an equipment's proclivity to respond at two or more frequencies at the same time. This fact alone indicates the wisdom of requiring a level of tolerance to random vibration and the use of a random vibration test in the qualification process.

A ship is a random vibration generator. Vibrations generated by the screw predominate, but many other sources contribute to the vibrations existing at any location on the ship. Motor-driven machines in the near vicinity provide vibrations near the fundamental and submultiples of the power line frequency. Fans and blowers produce pulsations at the passing frequency of their impellers. Gear trains (such as the massive main reduction gear) contribute vibrations at their tooth-meshing frequency. Ball bearings create vibrations at ball rotating, race rotating, and multiple relations of these element frequencies. Further, as the ship moves forward through the sea and rolls from side to side, the depth of the screw varies. The thrust on the screw changes and thereby the magnitude of the produced pulse and cavitation noise varies. The shipboard-recorded analog time-history in figure 20 shows the relative magnitudes of these various vibrations as measured at one point. Clearly, all but the largest may be ignored; usually the waveform created by the blades on the screw. Although vibrations at other frequencies contribute to the recording, the major randomness in this waveform is a result of the magnitude of the vibration created by the screw. In the absence of the other contributions, the vibrations created by the shaft and screw would be "narrowband" random vibrations that vary only in amplitude. Of course, as the ship changes speed, there is a change in the basic frequency of these vibrations so, over a much longer time period than is normally used in quantifying random vibrations, shipboard vibrations can be considered completely random.

In preparing a random-vibration description of the shipboard environment, data mentioned above (from references 3 and 4, and other vibration measurement programs) were subjected to acceleration spectral density analysis. A total of 7524 analyses were performed. Each analysis was drawn from four different time samples of recorded shipboard vibration. Figures 21 through 24 show the predominance of the blade passing frequency over other vibration sources. In the task discussed in NOSC TR 558 (reference 7), emphasis was placed on developing a random vibration description of the shipboard environment for use in laboratory tests in which reliability of equipment was being assessed. As is reported in reference 5, naval surface combatants were separated into the following five categories based on functions provided by the ships and by the missions often performed:

Category	Ship Types
I	PG, PGH, PHM
II	CV, CVN
III	DE, DD, DDG, FF, CG, DD 963, etc.
IV	LCC, LHA, LSD, LPA, LKA, LST, etc.
V	Unlisted types, or more than one of the above groupings

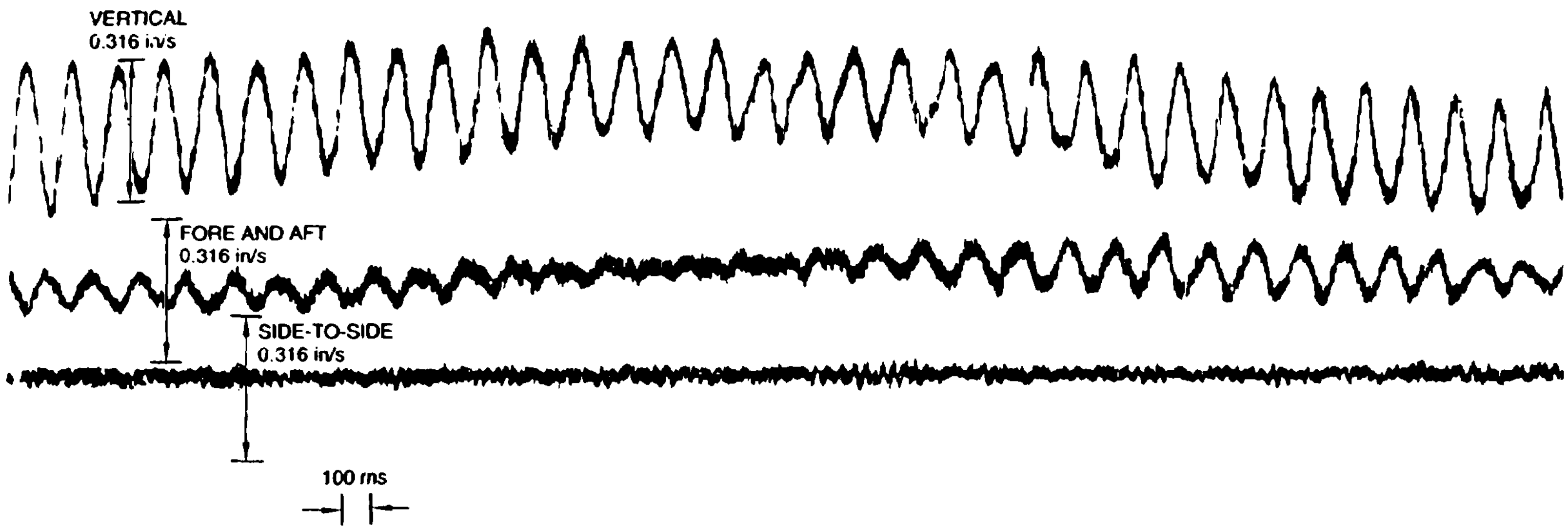

Figure 20. Randomness of shipboard vibrations.

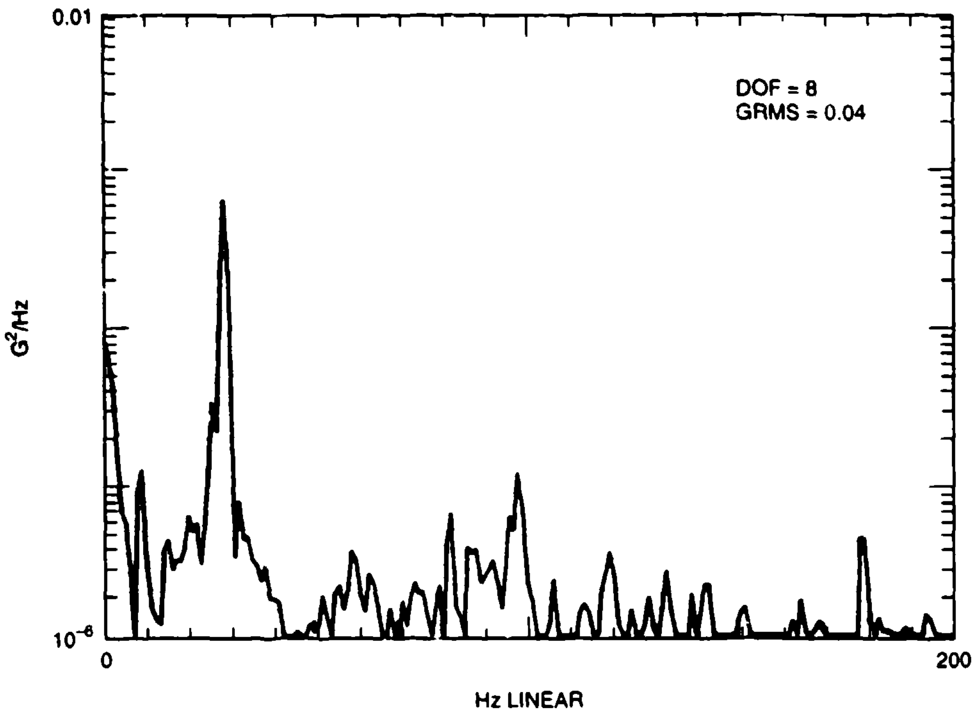

Figure 21. Representative acceleration spectral density analysis, PGH 2.

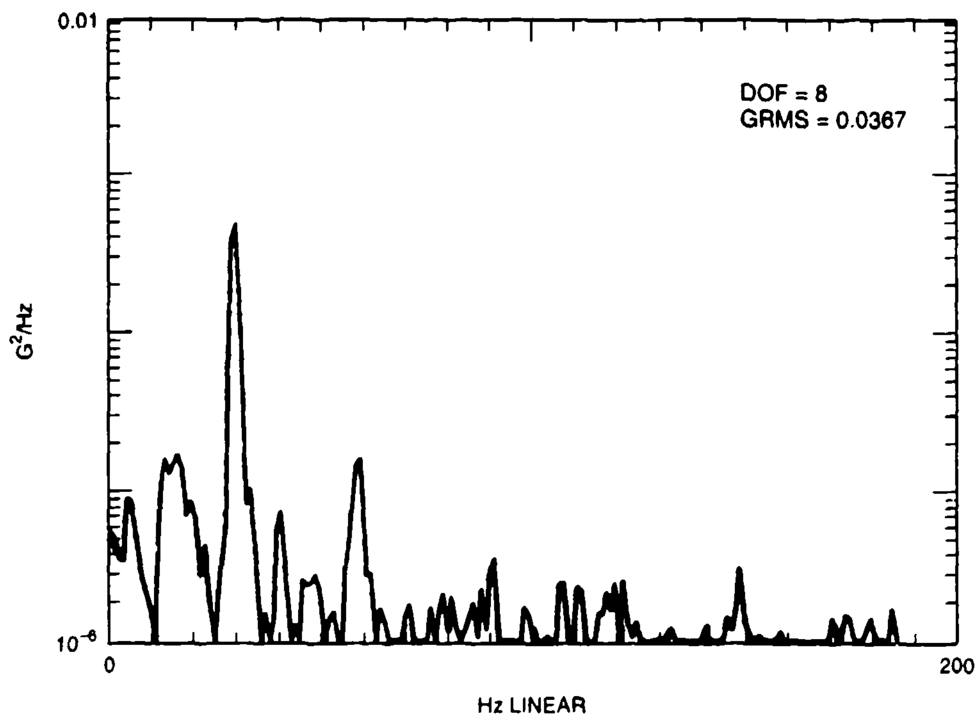

Figure 22. Representative acceleration spectral density analysis, DLG 24.

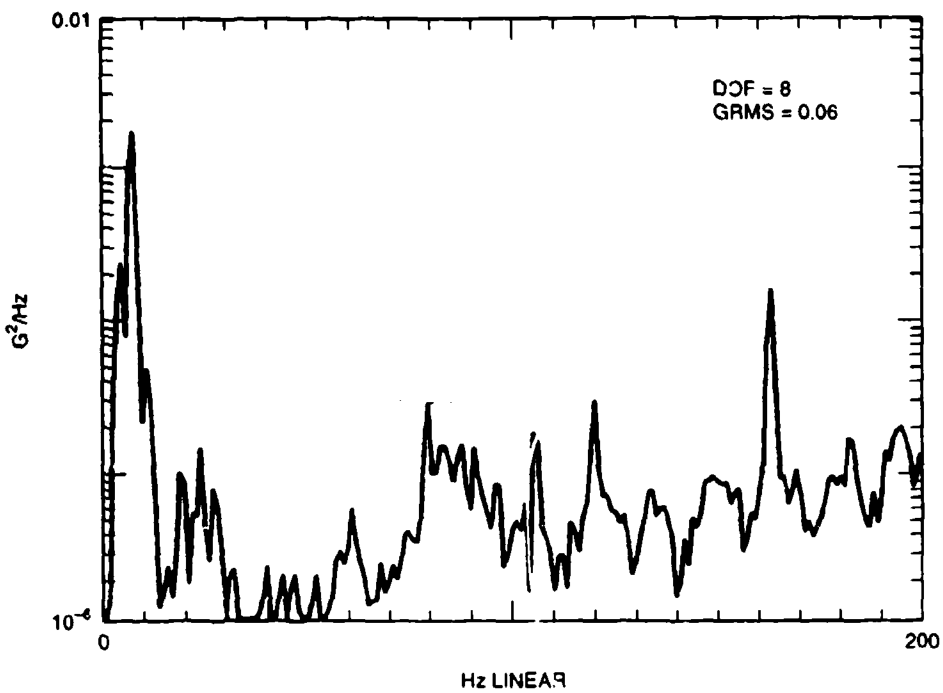

Figure 23. Representative acceleration spectral density analysis, DE 1070.

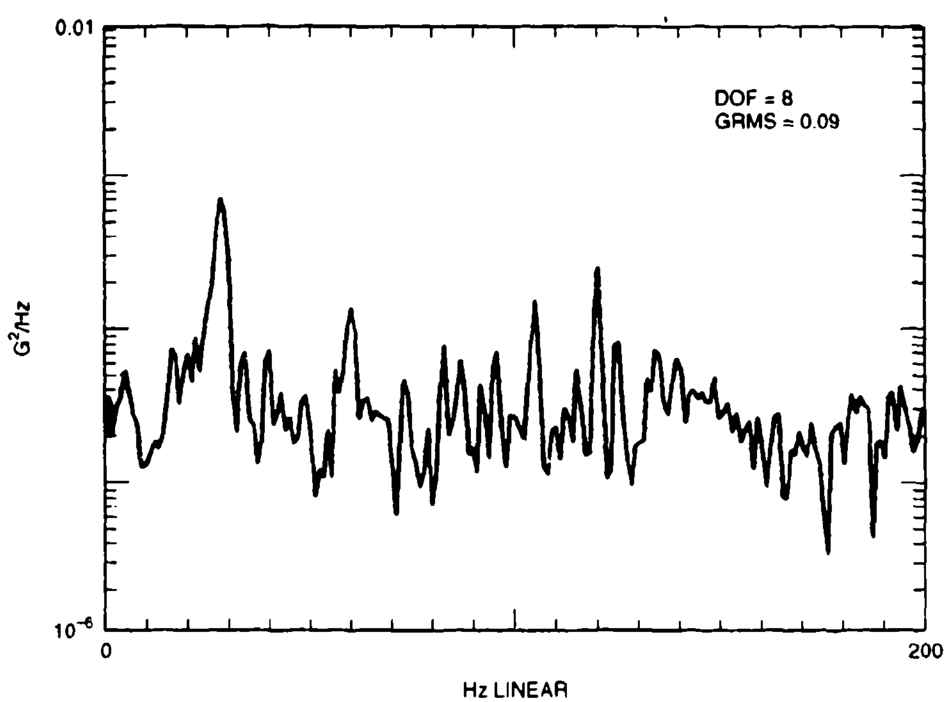

Figure 24. Representative acceleration spectral density analysis.

Development of the desired spectral densities for reliability testing is of interest but, because usual levels were desired, an averaging process was used. This resulted in levels considerably lower than those of interest in specifying what an item of shipboard equipment must endure. Statistical approaches must be used to describe random vibration. The term "random vibration" indicates that magnitude varies randomly from one period of time to the next. However, we can gather a number of samples of the vibration, calculate statistics on magnitude and frequency, and give our description in statistical terms. The term considered most informative is "acceleration spectral density" (see figures 21 through 24) in which averages of vibration magnitudes at various frequencies are shown. As is discussed in reference 8, the mathematics used to calculate acceleration spectral density provides valid estimates so long as the following constraints are observed: (1) the random process must be stationary; that is, the same results must be obtained if the same sampling period is used but with the time origin changed, and (2) the random process is ergodic; that is, each sample is representative of the group. Obviously, a stationary condition is never totally present since machines are not operated continuously. But we can limit our resulting description to that configuration existing when the samples were taken. Assuming these constraints are met, for our purposes, spectral density calculations are then valid for that configuration of vibration generators. Confidence in the validity of the spectral density calculation increases directly with the number of samples averaged. Each sample contributes two statistical degrees of freedom (DOF) to the measurement of validity.

Acceleration spectral densities developed in reference 7 suffer from being averaged too many ways to be other than just a passing interest here. Some of the recorded data were biased toward the higher vibration levels found on the various ships visited, but most of the recorded passages, particularly those from the unattended recorders, were taken on a timed basis. Recorded vibration levels were therefore often much lower than an operator would have seen fit to record (for example, when the ship was anchored or tied up at a pier).

For the task discussed in reference 7, the low-level passages were perhaps desirable. But even then the derived random vibration spectral densities should have been raised to account for the difference in test time and shipboard service life. However, we can make use of some of the work done in reference 7. Figure 25 (from reference 7) shows how the shape of the spectral density plots was obtained. Although no direct use of the ordinate amplitudes was made in reference 7, they were some of the higher ordinate values obtained in the data analysis, and for our purposes here, they are ideal. A spectral density plot can be developed for Category III ships by using the shape of reference 7 but with ordinate values from figure 25. A new root mean square (rms) value can be calculated. We then have a means of scaling up the spectra suggested in reference 7 for use in qualifying equipment for shipboard service.

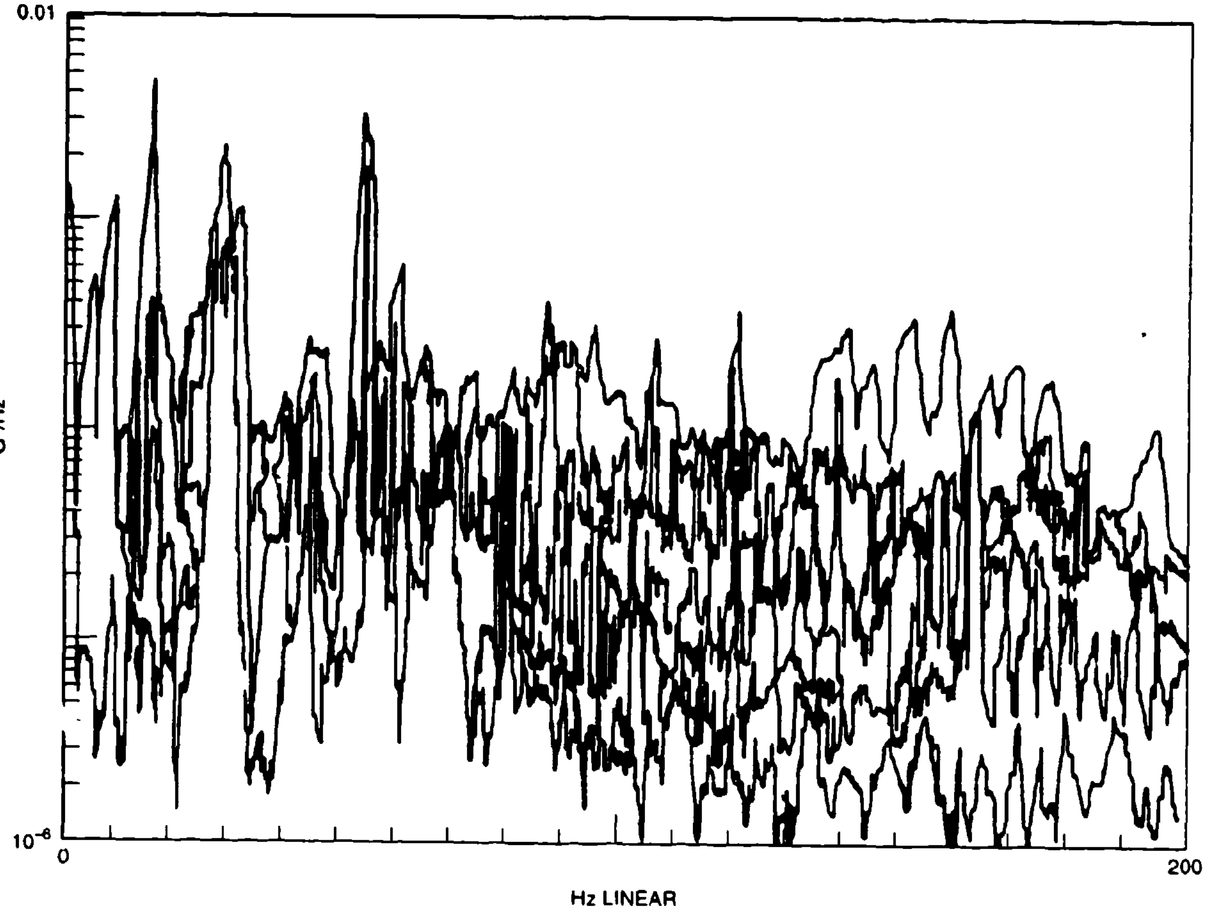

Figure 25. Representative composite spectrum.

Figure 26 is a spectral density plot for Category III ships with the same shape as that in reference 7, but with amplitudes based on figure 25. Notice that the rms value turns out to be 0.597 G, which is nearly 10 times the level suggested for reliability testing. Now we have a low-level vibration spectrum that could be expected to represent the peak random vibration one might encounter on Category III ships during normal operations. This is a random-vibration description equivalent in nature to the sinusoidal levels given by equation 1 above. Using a factor of 10 to upscale the other three spectral densities suggested in reference 5, figures 27, 28, and 29 are generated for Categories I, II, and V respectively. As in reference 7, Category V spectral density should be used for ships in Category IV due to insufficient data for that category.

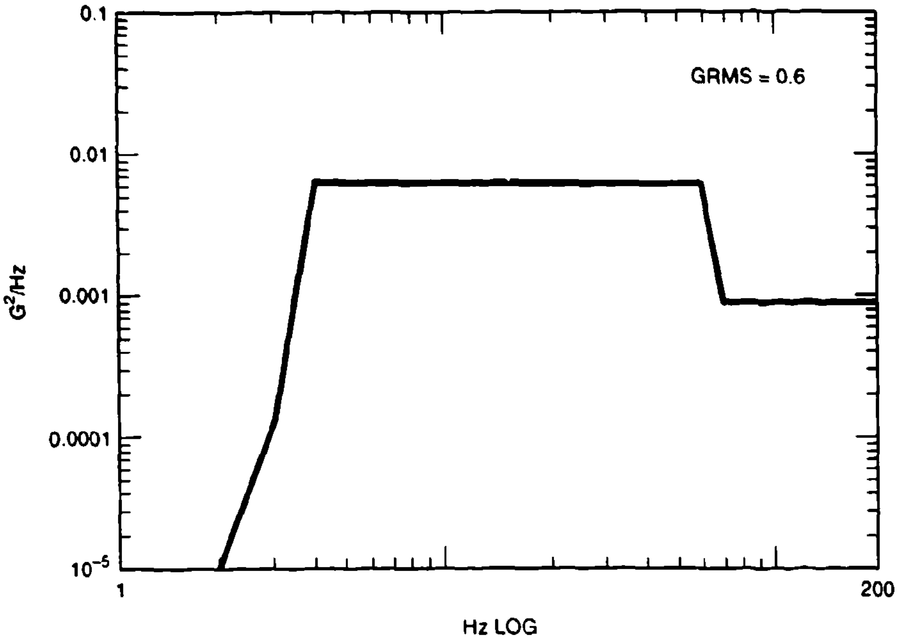

Figure 26. Spectral density plot for Category III ships.

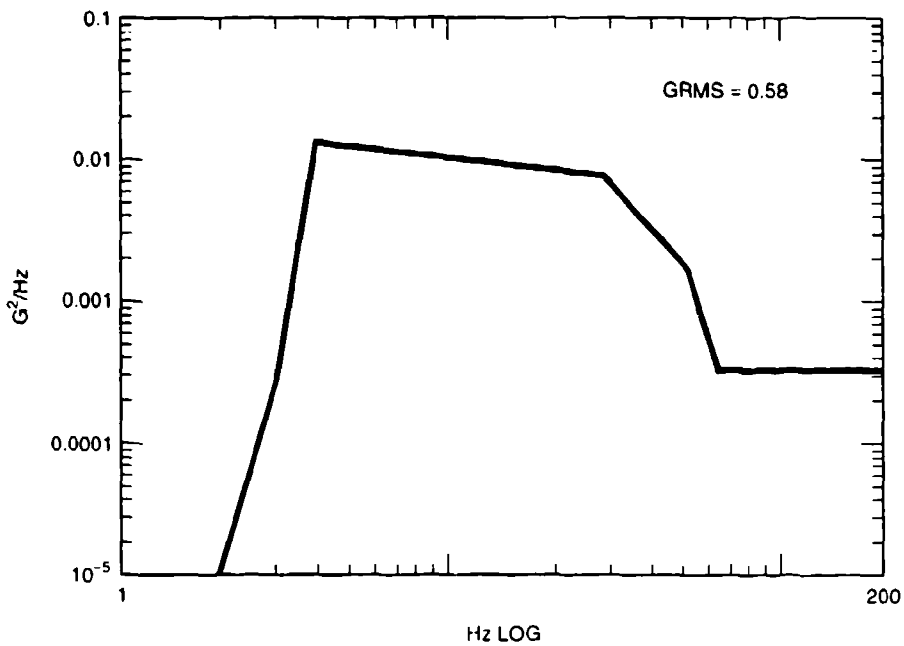

Figure 27. Spectral density plot for Category I ships.

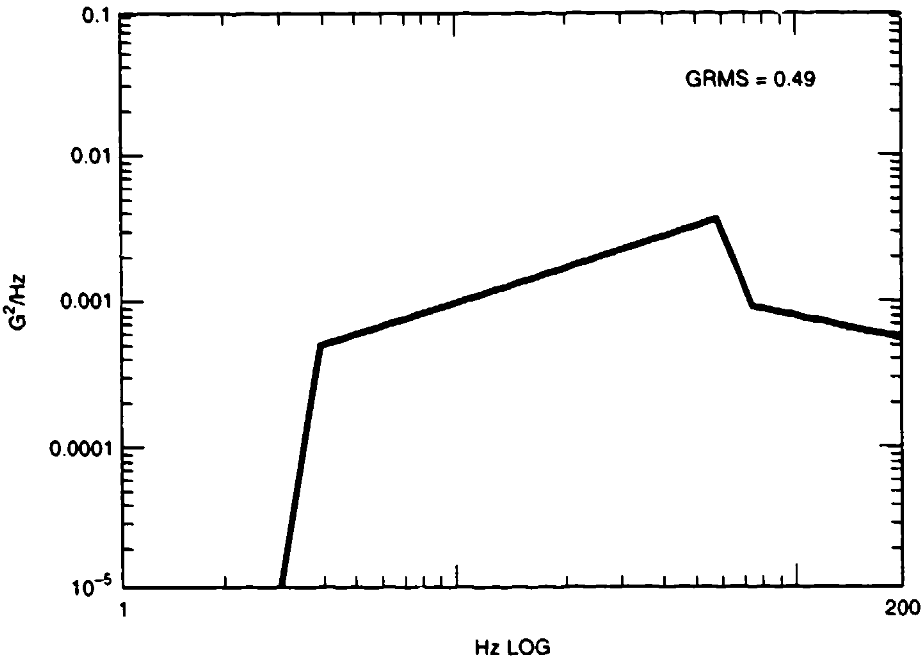

Figure 28. Spectral density plot for Category II ships.

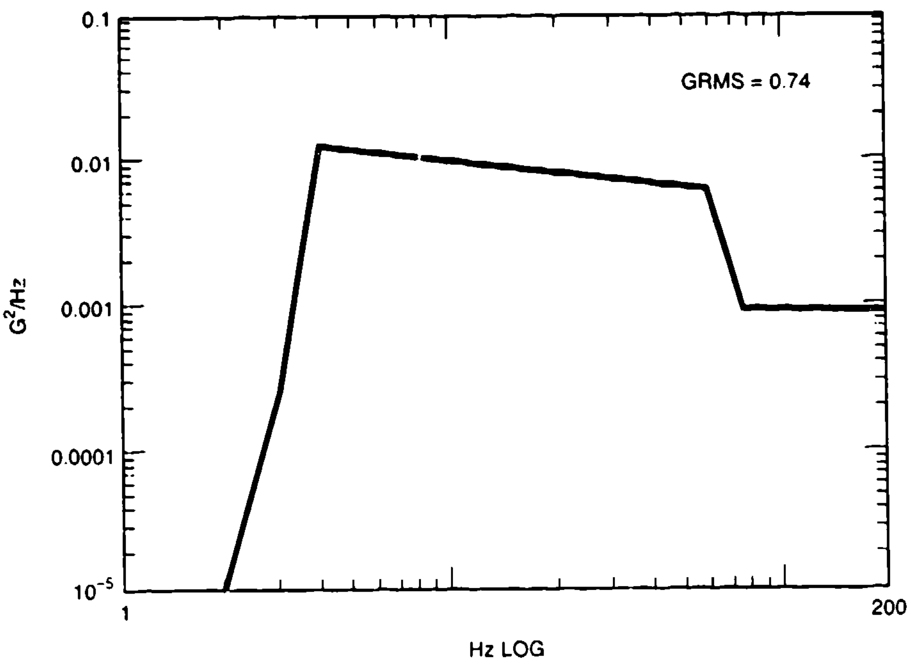

Figure 29. Spectral density plot for Category V ships.

VIBRATION SPECIFICATION

We now have enough information to suggest vibration requirement packages for shipboard electronic equipments that are based on measured low levels. The equipments, when exposed to single-frequency vibration at levels described in equations 1 and 2, or the random vibration shown in figures 26 through 29, should perform flawlessly. These levels are much lower than might be the case when a ship has suffered battle damage or when urgency mandates maneuvers causing high-level vibrations. Because of this, users of these minimal-level requirements should be critical when judging acceptability of the equipment. The ability of the equipment to tolerate vibration should be demonstrated under the testing regime given in appendix A (a separate bank of tests should be applied in each major operational state). The test description in appendix A is patterned after MIL-STD-167. It may be included intact in procurement documents or modified as necessary to accommodate the criticality of the equipment being procured.

EQUIPMENT CRITICALITY AND VIBRATION TOLERANCE

Appendix A can be used as a suggested vibration requirements package suitable for non-mission-critical shipboard equipment. However, all equipment procured for shipboard use will not be minimal in criticality. What relationship should exist between criticality and vibration tolerance? We will assume vibration tolerance of the equipment (and thereby its cost to produce) should increase in direct proportion to the criticality of the equipment, with MIL-STD-167 levels considered an upper bound except for certain special cases.

We will not propose a method of judging relative criticality of various electronic equipment or its application, except to point out that the levels above represent roughly one-tenth of what MIL-STD-167 requires. If criticality were judged on a numerical basis from 1 to 10, the numeric criticality descriptor could be used directly as a multiplier for the single-frequency levels given above, and equipment with ruggedness roughly equal to the criticality of the application should result. Notice that the square of the numeric criticality descriptor (multiply by 25 to obtain 5 times test level for a criticality descriptor of 5) would have to be applied to the random vibration spectral values to obtain the same scaling of requirements and test and ruggedness.

TEMPERATURE AND HUMIDITY

Extreme temperature and humidity environments in which ships operate are reasonably well described in MIL-STD-210 (reference 9). Anchorage, Alaska, was chosen in the standard to represent the world's lowest temperature navigable port, while Adaban, Iran, was chosen to represent the hottest. Absolute humidity extremes (1 percent) associated with these are 133 and 30,000 parts per million (ppm), water vapor to dry air, respectively. Reference 9 further states that Belize City, Belize, experiences the highest constant absolute humidity level, exceeding 25,000 ppm in excess of 20 percent of the time. Dew points associated with these three absolute humidities are -35°C, 31°C, and 28°C, respectively. (Dew point is the temperature at which moisture condenses out of a mass of air if a volume of that air is cooled while pressure is held constant). While these values of absolute humidity are of impressively high and low extremes, they do not pose much of a problem.

Another commonly used measure of humidity, relative humidity (RH), may provide a better assessment of possible difficulty. RH is a dimensionless parameter that relates how much moisture a body of air contains compared to how much it could contain at that same temperature and pressure. With this parameter, the dew points mentioned above are the temperatures at which air at those absolute humidities reaches 100 percent RH, and condensation starts to occur.

Both electronic equipment and humans thrive in environments ranging from 30- to 90-percent RH. When local RH gets much below 30 percent, humans tend to grow chilled in what ordinarily are considered comfortable temperatures. Humans develop itchy skin, dry nasal membranes, and become distracted by the effects of static electricity. Electronic equipment experiences problems with clinging paper, accumulates more dust than usual, and may have sensitive components destroyed by electrostatic discharge. How, in the normally humid marine environment, can RH on a ship go below 30 percent? It can happen anytime external air with a temperature less then 36°F (2.2°C) is brought into the ship and heated to the human comfort zone.

Low moisture content in the air makes the human body's evaporative cooling system more efficient and thereby causes the "chilled" feelings mentioned above. It is likely that temperature in a space will be raised to offset the "chill" perceived by humans. Electronic equipment cooling systems do not feel a "chill" in response to low RH as do humans. Low moisture content only slightly decreases efficiency of non-evaporative cooling processes, such as convective heat transfer often used in electronics, but it exacerbates problems that electronics experience stemming from static electricity. Further, the temperature increase required by the human operators means an upward shift in the operating temperature of the electronics, and a likely loss of reliability.

Though problems exist at low RH, the high end of the RH range presents a considerably greater problem potential for both humans and electronic equipment. For humans, the body's evaporative cooling system operates with decreased efficiency. At low temperatures, decreased efficiency is not too noticeable. At high temperatures, though, decreased evaporative cooling efficiency detracts from the body's ability to regulate its temperature. This places stringent limits on human activity and will lead humans to insist on lowered space temperatures. At both high and low temperatures, fungal diseases thrive in the high humidity environment. They quickly become a factor in accounting for elements contributing to reduced human output.

In contrast to the human body, electronic equipment does not suffer from decreased cooling system efficiency. In fact, the increased amount of moisture in the cooling air slightly increases cooling system efficiency. In addition, the lowered space temperatures required by human occupants lowers the operating temperatures of the electronic equipment, a move that is generally known to enhance reliability of the electronics. As long as the electronic equipment contains no fungal nutrient or strongly hygroscopic (water absorbing) materials in its construction, a highly humid environment should present few problems for electronic equipment.

While discussing high RH environments, note that air chilling equipment is in use on most Navy ships. As with air conditioners used in many homes, shipboard air chillers make little or no attempt to control the relative humidity of the chilled air. At sea, ambient air is often warm and humid and when chilled to the desired temperature for injection into a compartment, it is near saturation. Reference 7 discusses temperature and humidity measurements made in temperature controlled shipboard compartments:

> Human comfort requirements place a definite low limit on temperatures. By whatever means available, (unit heaters, shut down or modulation of chilled air supply), temperatures are kept to a range of 50 to 77°F (10 to 25°C)..... relative humidity is always high in temperature controlled spaces when ship's ambient air is hot and reasonably moist. It ranges from 48 to 95 percent depending on the mix of outside air to recirculated air, and on the proximity to the exhaust of the chiller.

It should be noted, though, that the temperature of 50°F did correspond with the 95-percent RH, and that the condition existed only at the discharge from the chilled air duct. As the chilled air moved into the compartment and picked up some of the heat load, its temperature and humidity moved toward more normal values.

Many commercial test instruments claim the ability to operate in and survive a 90-percent RH, noncondensing environment. That they can survive under those conditions is more readily understood when you determine that 70°F (21.1°C), 90-percent RH air drawn into the instrument for cooling could become, with a sufficient heat load, 80°F (26.7°C), 65-percent RH air. The waste heat actually improves the humidity environment. Note, though, the "noncondensing" qualifier used in their specifications.

Reference 9 provides hourly data for a high absolute humidity (1-percent value) condition near Abadan, Iran (table 1), in which moisture content varied between 26,000 and 30,000 ppm while temperature varied between 88 and 105°F (31 to 41°C). RH, however, never rose above 88 percent. Hourly data presented for Belize City, Belize (table 2), describing the highest sustained humidity, discloses moisture content varying between 22,000 and 24,000 ppm, and temperature varying between 81 and 86°F (27°C and 30°C). In this case, the RH ranged from 91 to 94 percent, but condensation occurred in what reference 9 called the "High Relative Humidity with High Temperature Daily Cycle" (provided in table 3). The conditions listed in this cycle occur 1 percent of the time and can be expected in waters near Calcutta, Nanking, Kwajalein Atoll, Seno (Laos), Papua New Guinea, Guyana, Kampot (Cambodia), Paramaribo (Surinam), Vietnam, and similar tropical oceans. The range of moisture content in this listing is between 21,400 and 26,000 ppm, while temperature varied between 79 and 95°F (26 to 35°C). What is remarkable in this listing is that RH varied between 74 and 100 percent and held at 100 percent for 6 hours or more.

Condensation occurs whenever air is cooled to its dew point or below which, for 80°F, 90-percent RH air, is only 77°F (26.7°C and 25.0°C respectively). These conditions can happen readily on a ship. Presume the mechanical refrigeration, which has been performing flawlessly, has kept the temperature in a compartment filled with electronics at 70°F for several days. Every thing in the compartment that is not actively producing heat has stabilized at 70°F. Suddenly, the air chilling system fails, and temperatures begin to rise in the compartment. When temperatures reach the point that alarms are triggered in the installed equipment, doors will be opened, and moist, warm, marine air (say 80°F, 90-percent RH), will be introduced into the compartment to bring temperatures back within bounds. When that air strikes any of the cooled surfaces, condensation occurs immediately and continues until enough moisture has chilled out of the marine air to lower its dew point to the temperature of the compartment and the electronic equipment. Of course, as the temperature of the marine air is lowered, the surfaces and items in the compartment rise in temperature until equilibrium is again reached. Where does all the moisture go that has been chilled out? It's on all the formerly cool surfaces and inside the formerly cool electronics! What were once cool and reasonably dry are now a little warmer and extremely wet. The heat-generating items whose internal temperatures exceeded the dew point of the suddenly introduced marine air probably did not suffer internal condensation. Its a safe bet, though, that like everything else in the compartment, all its nonheated and external surfaces are wet.

Table 1. High absolute humidity.

TIME (LST)	ABSOLUTE HUMIDITY MIX. RATIO (ppm)	DEW POINT (^{0}C)	DEW POINT (^{0}F)	TEMPERATURE (^{0}C)	TEMPERATURE (^{0}F)	R.H. (%)	SOL. RAD (W/m^2)	SOL. RAD (Bph)
01	26×10^3	29	84	31	88	88	0	0
02	26×10^3	29	84	31	88	88	0	0
03	26×10^3	29	84	31	88	88	0	0
04	26×10^3	29	84	31	88	88	0	0
05	26×10^3	29	84	31	88	88	0	0
06	27×10^3	29	85	32	91	88	45	15
07	28×10^3	30	86	34	93	83	315	100
08	29×10^3	31	87	36	96	78	560	177
09	30×10^3	31	88	37	98	73	790	251
10	30×10^3	31	88	38	100	70	950	302
11	30×10^3	31	88	39	102	66	1035	328
12	30×10^3	31	88	40	104	63	1080	343
13	30×10^3	31	88	41	105	60	1000	317
14	30×10^3	31	88	41	105	60	885	280
15	30×10^3	31	88	41	105	60	710	225
16	30×10^3	31	88	41	105	60	465	147
17	29×10^3	31	88	39	102	64	210	66
18	29×10^3	31	87	37	99	69	15	4
19	28×10^3	31	87	36	97	74	0	0
20	28×10^3	30	86	34	94	79	0	0
21	28×10^3	30	86	33	91	85	0	0
22	27×10^3	29	85	32	90	86	0	0
23	26×10^3	29	85	32	89	87	0	0
24	26×10^3	29	84	31	88	88	0	0

Notes: (1) Mixing ratios are based upon a typical surface atmospheric pressure of 1000 mb and dew points in adjacent column.

(2) Parameter Ranges:

Absolute Humidity	$26.0\text{–}30.0 \times 10^3$ ppm
Dew Point	29–31^{0}C (84–88^{0}F)
Relative Humidity	60–88 percent
Temperature	31–41^{0}C (88–105^{0}F)

(3) The data in the table pertain to Abadan, Iran.

Table 2. High sustained absolute humidity.

TIME	ABSOLUTE HUMIDITY			TEMPERATURE		R.H.	SOL. RAD	
	MIX. RATIO	DEW POINT						
(LST)	(ppm)	(°C)	(°F)	(°C)	(°F)	(%)	(W/m^2)	(Bph)
01	22×10^3	27	80	28	82	91	0	0
02	22×10^3	26	79	28	82	92	0	0
03	22×10^3	26	79	28	82	92	0	0
04	22×10^3	26	79	28	82	93	0	0
05	22×10^3	26	79	27	81	93	0	0
06	22×10^3	26	79	27	81	94	45	15
07	22×10^3	26	79	28	82	93	230	73
08	23×10^3	27	80	28	82	93	435	138
09	23×10^3	27	80	29	84	92	630	200
10	24×10^3	28	82	29	84	92	795	252
11	24×10^3	28	82	30	86	91	900	286
12	25×10^3	28	83	30	86	91	970	307
13	25×10	28	83	30	86	91	970	307
14	24×10^3	28	83	30	86	91	900	286
15	24×10^3	28	83	29	84	91	795	252
16	24×10^3	28	82	29	84	91	630	200
17	24×10^3	27	81	29	84	91	435	138
18	23×10^3	27	81	29	84	91	230	73
19	23×10^3	27	81	29	84	91	45	15
20	23×10^3	27	81	29	84	91	0	0
21	23×10^3	27	81	29	84	91	0	0
22	23×10^3	27	80	29	84	91	0	0
23	23×10^3	27	80	28	82	91	0	0
24	23×10^3	27	80	28	82	91	0	0

Notes: (1) Mixing ratios are based upon a typical surface atmospheric pressure of 1000 mb and dew points in adjacent column.

(2) Parameter Ranges:

Absolute Humidity	$22.0\text{–}24.0 \times 10^3$ ppm
Dew Point	26–28°C (79–83°F)
Relative Humidity	91–94 percent
Temperature	27–30°C (81–86°F)

(3) The data in the table pertain to Belize City, Belize, during August.

Table 3. High relative humidity combined with high temperature.

TIME	ABSOLUTE HUMIDITY			TEMPERATURE		R.H.	SOL. RAD	
	MIX. RATIO	DEW POINT						
(LST)	(ppm)	(°C)	(°F)	(°C)	(°F)	(%)	(W/m²)	(Bph)
01	22.3×10^3	26.7	80	27	80	100	0	0
02	21.6×10^3	26.1	79	26	79	100	0	0
03	21.6×10^3	26.1	79	26	79	100	0	0
04	21.6×10^3	26.1	79	26	79	100	0	0
05	20.7×10^3	26.1	79	26	78	100	0	0
06	20.7×10^3	26.1	79	26	78	100	45	15
07	21.7×10^3	26.4	79.5	27	81	94	230	73
08	22.6×10^3	26.7	80	29	84	88	435	138
09	23.1×10^3	27.2	81	31	87	82	630	200
10	24.0×10^3	27.8	82	32	89	80	795	252
11	25.4×10^3	28.6	83.5	33	92	77	900	286
12	26.1×10^3	29.4	85	34	94	75	970	307
13	26.1×10^3	29.4	85	34	94	75	970	307
14	25.9×10^3	29.4	85	35	95	74	900	286
15	25.9×10^3	29.4	85	35	95	74	795	252
16	25.9×10^3	29.4	85	34	93	77	630	200
17	25.7×10^3	28.9	84	33	92	79	435	138
18	25.4×10^3	28.9	84	32	90	82	230	73
19	24.9×10^3	28.6	83.5	31	88	86	45	15
20	24.1×10^3	28.6	83.5	29	85	91	0	0
21	23.6×10^3	27.5	81.5	28	83	95	0	0
22	23.4×10^3	27.5	81.5	28	82	97	0	0
23	22.9×10^3	27.1	80.7	27	81	98	0	0
24	22.3×10^3	26.7	80	27	80	100	0	0

Notes: (1) Mixing ratios are based upon a typical surface atmospheric pressure of 1000 mb and dew points in adjacent column.

(2) Parameter Ranges:

Absolute Humidity	$20.7\text{–}26.1 \times 10^3$ ppm
Dew Point	26–29.4°C (79–85°F)
Relative Humidity	74–100 percent
Temperature	26–35°C (79–95°F)

(3) The data in the table pertain to moist tropic areas:
Dobochura, Papua New Guinea; Calcutta, India; Hanoi, Viet Nam; Nanking, China; Kwajalein Atoll, Seno (Laos); Kampot (Cambodia); Paramaribo (Surinam); Georgetown, Guyana.

Another way in which condensation may happen is through radiant heat transfer. For condensation to occur on a surface, the surface must be colder than the surrounding air. For example, automobiles collect dew during the night through radiant heat transfer. One would think that the metal of an automobile, surrounded by natural air would not have a chance to become colder than the air. A body of warm air might cross the area after the automobile had stabilized at a lower temperature, but air temperature over large areas is generally constant and such an event is not likely. Horizontal surfaces are the first to become wet, and as time goes by, the wetting proceeds to less horizontal, and finally to nearly vertical surfaces. Also, dew seldom forms on surfaces sheltered from a direct view of the outer sky (e.g., a carport, the branches of a tree, or clouds) The cooling mechanism here is radiation. The surfaces with the most direct path (least resistance to radiant heat transfer) to the outer sky cool to the dew point first, and other surfaces follow along as time makes up for their longer path. As long as the path is not blocked, this process continues, sometimes reaching the point where ice is formed even though the air temperature has not dropped to freezing. This type of condensation is not likely to occur on equipment located inside a ship, but if a cool black surface exists near a planned interior mounting location, condensation on the installed equipment due to radiant heat transfer is possible.

Temperature and humidity measurements were made during the shipboard environment measurement program reported in reference 3. A high temperature of 122°F (50°C) was measured during the program in the AEW (Aircraft Early Warning) Room on the USS *Hancock* (CVA 19), but as was discussed in references 3 and 7, that temperature was caused by inadequate air circulation in the compartment. The situation was easy to correct and was one which an equipment design should not have to accommodate as a usual environment. Because it was almost certain that the measurement program would not be performed with local area temperatures at extremes, sensors were installed so as to document differences in temperature between air entering and exiting a particular compartment. With documented temperature rises, we could then determine what the compartment temperatures would probably be under whatever extreme ambient temperatures the ship might experience. Except for the AEW Room on the *Hancock*, no temperature rises exceeding 22°F (12°C) were found. Using the Persian Gulf 20-percent high temperature of 109°F (43°C) from reference 9 (a temperature that is exceeded 20-percent of the time), one could expect temperatures of 131°F (55°C) in the electronic spaces on ships with similar temperature rises.

While the temperature calculated above appears unusually high at first glance, remember that it represents the temperature of the air exiting an electronics compartment. This is air that has completed a cooling pass through the installed electronics. Good design requires precluding air of this temperature being drawn into other equipment for cooling. Also remember that the 22°F temperature rise was measured in electronic compartments where no air chilling was employed. In an air-chilled compartment, inlet temperatures were measured as low as 50°F (10°C), and often were found at around 65°F (18°C). With these inlet temperatures, air leaving the compartment would range from 72 to 87°F (22 to 31°C).

One important conclusion drawn from the measurement program, plus the following review of published humidity data, is that high temperature and high RH seldom coincide. Figure 30 displays the relationship inherent in data measured for the studies reported in reference 3, and tables 1, 2, and 3 show high temperatures existing only when RH is depressed. It is possible the 95-percent RH with the coincident 122°F (50°C) temperature called for in usual shipboard specifications might be encountered in engineering spaces where steam is vented. Also, it may be found in electronics spaces after battle damage and fire fighting, but the chances of these coincidences are slim. Only the most critical of shipboard electronics should be required to tolerate such unusual events.

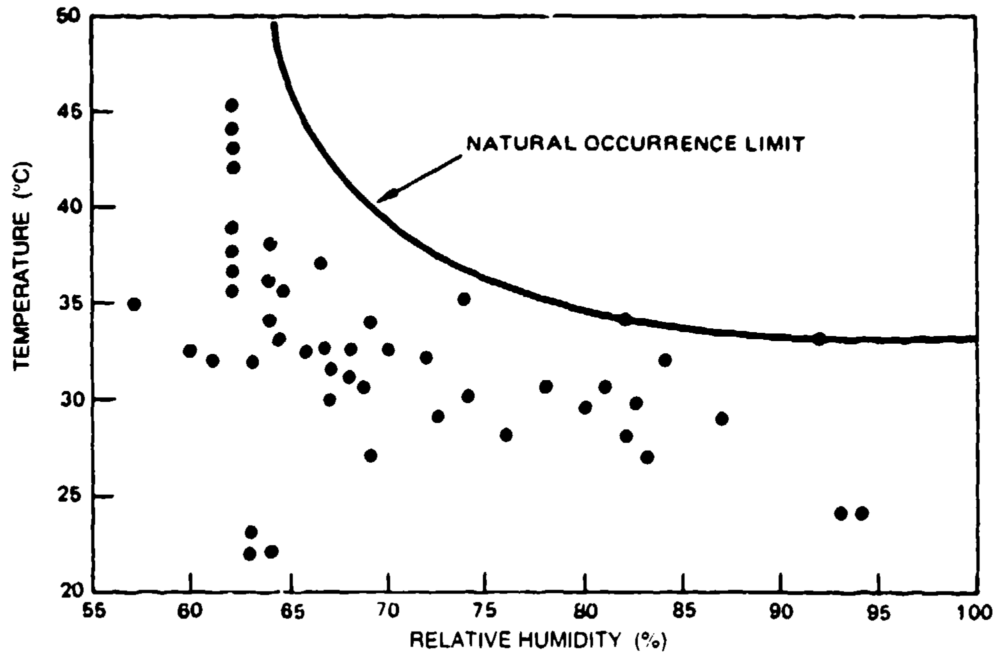

Figure 30. Measured temperature and humidity occurrences.

Three major types of temperature-humidity environments are evident in the shipboard mounting of electronic equipment. There are (1) the compartments in which chilled air is available to aid in carrying away waste heat, (2) compartments in which only ship's ambient air is available, and (3) mounting locations external to the ship. Keeping in mind that air chillers are far from being perfectly reliable, and using the above temperatures and humidities, with the natural relationship between them, three temperature and humidity (T&H) test cycles were established. Figures 31, 32, and 33 show the time relationships for the various T&H values. Note that each test is 1 week in length. Six days of each cycle represent usual environments, and the seventh represents the extremes that can be expected due to weather variations, battle damage, or machinery failure (heaters or air chillers). For equipment not critical to the ships mission, power could be applied to the equipment under test all through the humid parts of the cycle for the drying effect and performance allowed to wander outside of tolerance during temperature extremes. Power could even be secured during high temperatures. As the criticality of the equipment rises, though, adherence to all aspects of the T&H cycles should be required.

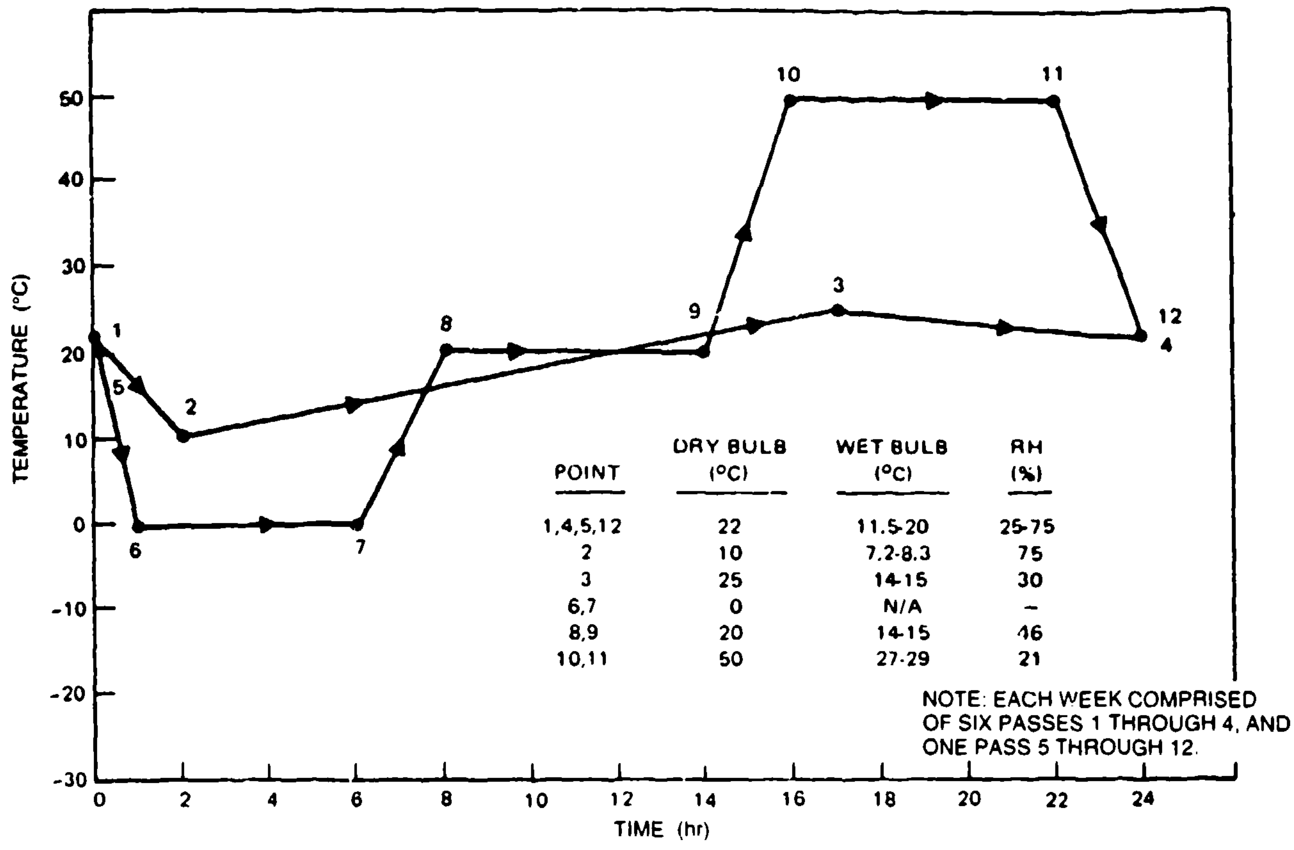

Figure 31. T&H Cycle I (internally mounted, temperature controlled).

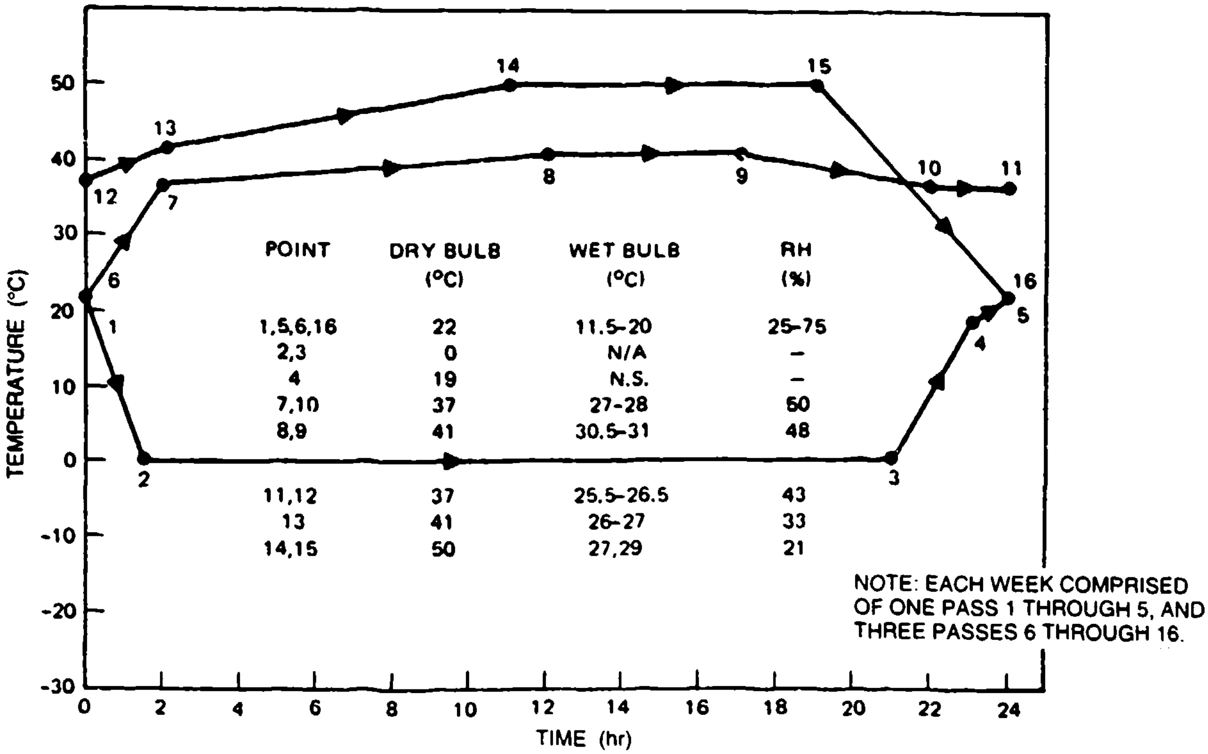

Figure 32. T&H Cycle II (internally mounted).

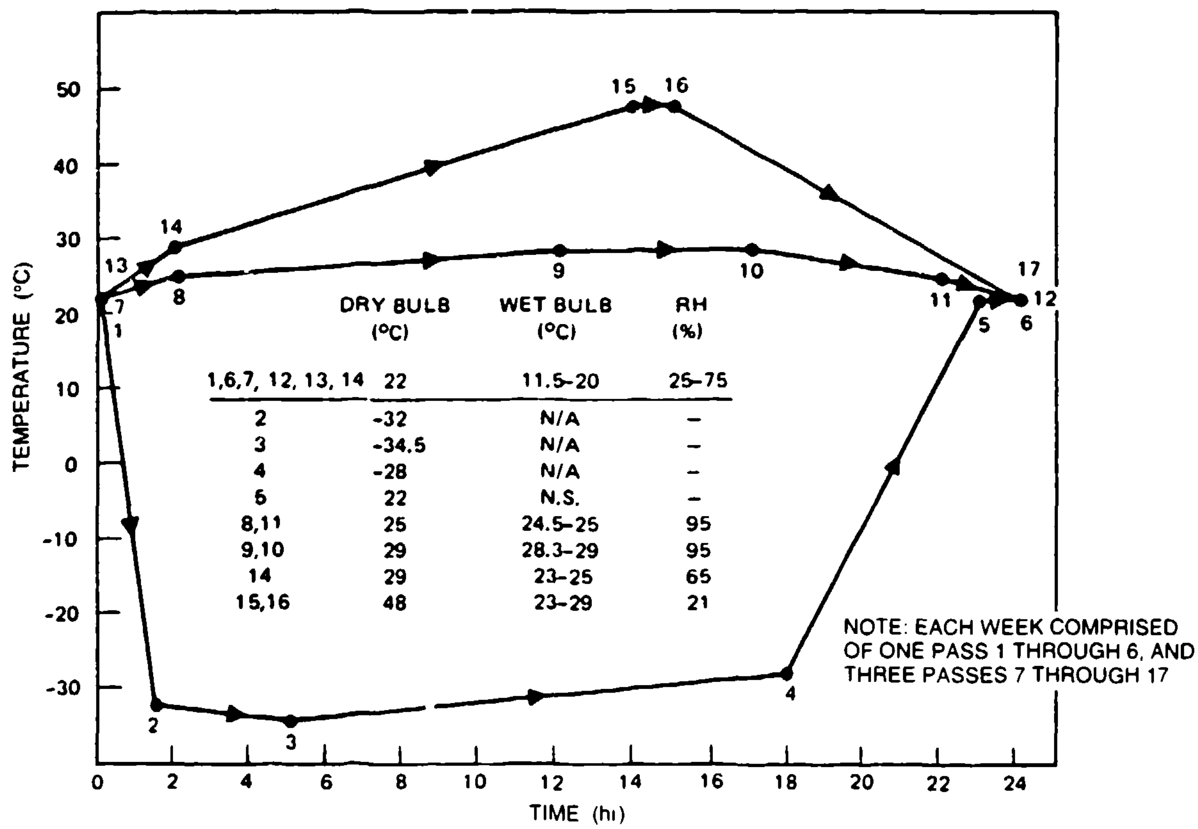

Figure 33. T&H Cycle III (externally mounted).

MECHANICAL SHOCK

Mechanical shock is a dynamic disturbance that is short relative to the natural frequency of the system being excited. Under that definition, Navy ships have a high probability of being rich shock sources for installed electronic equipment.

Shock on a ship can result from many sources. Some of the apparent sources are not of great concern, due to the magnitude or length of time, of the energy release. Collisions, traumatic as they are, and in spite of the severe resulting damage, actually cause negligible levels of shock due to the relatively long rise time of the generated forces. The handling of cargo, such as provisions, boats, military vehicles and so on, sets up situations that can readily result in mechanical shock. But energy released in rough handling (even dropped items) of cargo is relatively small. As is the case for collisions, cargo handling does not often cause sudden transient motions to be generated and propagated throughout the ship.

On the other hand, the firing of the ships weapons (chaff launchers, guns, and missiles) and operation of the catapults and arresting gear on carriers, cause sudden transient motion (shock) levels that pose potential problems for installed electronics. These are discussed in the following subparagraphs:

a. Recoil forces from large guns present little or no difficulty due to excellent design of the recoil systems. In the task reported in reference 3, problems were reported with shipboard equipment dealing with ownship gunfire shock, but most of the troubled equipment (none of it electronic) suffered from the effects of muzzle blast, rather than recoil shock. All of the troubled equipment was mounted external to the superstructure or on the inside of bulkheads or the undersides of decks exposed directly to muzzle blast. Measured shock levels from gun recoil on decks and internal bulkheads were all less than 1 G.

b. Chaff launchers were not installed on ships on which measurements were made, so hard data are not available here. Subjectively, response of the ship's structure to the firing of the launchers is much less than that of a low-level underwater near-miss explosion. If electronic equipment being procured must be mounted within 30 feet of a chaff launcher, it would be prudent to establish the shock environment created by the launcher and require appropriate tolerance of the equipment.

c. Like recoil mechanisms, arresting gear on carriers is well designed and creates no appreciable general shock environment. Catapults, however, are not as well behaved. Water brakes at the forward end of each catapult bring the moving mass of the catapult to rest in a very short distance. A radar repeater mounted in Secondary Conn on the *Hancock*, a compartment located just below the flight deck and between the two forward catapults, experienced difficulty with the water brake shock. The repeated shocks continuously knocked the repeater out of calibration, even though the repeater was installed on "shock mounts." Two observations need to be made about this particular situation. First, there is seldom any need to install electronic equipment in such a location; second, the shock mounts amplified the shock environment for the repeater. Properly designed and installed mounts have no difficulty in providing the necessary shock isolation.

d. Deployment of mines and depth charges created serious levels of shock in after sections of ships in the past. A saving facet in this case is that little electronic equipment was needed in the after part of the ship where much of the shock creating activity was located. Modern methods reduce the probability of shock from this sort of activity.

Whenever shock-producing activities are part of the ship's mission, considerable engineering effort is expended to make certain that either shock levels are kept to acceptable levels, or that equipment is hardened for, or isolated from, the shock environment.

Hostile operations, though, pose a threat we cannot handle as we handled self-generated shock environments. Incoming shells, missiles, and bombs that manage to evade the ship's defenses and impact or explode on or near the ship's structure cause extensive local damage. Ammunition and fuel carried on board are sometimes set off explosively as direct secondary responses or at a later time due to fires. All these shock sources release relatively large amounts of energy. They create intense local damage and cause sudden, heavy transient motions that radiate in all directions from the point of generation or impact. Damage, with intensity dropping as distance increases, is conveyed by the transient motion and by air coupling.

To some extent, these explosive motions of the ship's structure obey the same laws of propagation as vibration in that structural spring constants control the magnitude of motion and distance over which the motion is transmitted. But, in contrast to vibration, stress levels are much higher in the ship's structure, particularly at locations near the point of impact. A large amount of the explosive energy is absorbed in plastic (non-elastic) bending of the ship's structure. It is characteristic of these above-water explosions that extensive damage is incurred locally, while little or no plastic damage can be seen tens of feet away.

Near-miss underwater explosions, from mines, bombs, missiles, or projectiles, create a different effect. Seawater is relatively incompressible, and it couples the energy from the underwater explosion into the hull of the ship with greater efficiency than does air in the above-water near misses. Further, it involves larger portions of the ship. While the near-miss underwater explosion may not cause the intense local damage of an above water hit, it creates heavy transient motion of the whole ship with accompanying ship-wide damage.

Direct underwater hits, from mines or torpedoes, cause intense local damage as do the above-water direct hits, but these further complicate the situation in that the whole hull of the ship is given a heavy transient motion at the same time. Unless machinery and systems on the ship have been shock hardened, it is probable that damage control will have to take place in darkness, with hand-operated tools, and with only spoken communications.

The usual peacetime cruising environment for Navy ships does not include many events involving explosions of any magnitude. Except in testing for shock hardness, an event reserved for usually only one of the earliest ships of a class, shock from heavy explosions rarely occur outside of wartime conditions. But, because we cannot predict when a shock might be visited on a ship, or when hostile acts may take place, we must prepare for it, and remain prepared, if damage is to be minimized and the ship is to remain an asset. All electronic equipment installed on a Navy ship must be designed and tested to ensure safety under levels of shock that a ship might encounter. At a minimum, even non-mission-critical equipment must demonstrate that it will not break its mountings, shed parts or otherwise create hazards for personnel or nearby critical equipment. The importance of the equipment to the ship's mission will range from non-mission-critical to mission-critical, and varying degrees of shock tolerance should be demanded. The minimum, though, should always be that just stated; that is, it shall not become a hazard to personnel or to nearby critical equipment.

MIL-S-901D (reference 10) describes tests and machines that are employed to investigate an item's ability to tolerate shock, particularly the shock resulting from underwater blast. Energy levels specified in MIL-S-901D do not necessarily simulate the maximum shocks a ship might encounter, but just a level that the ship could be expected to survive with hull intact. As was the case with vibration levels of reference 2, if suppliers of the equipment take responsibility for ensuring that the equipment tolerates levels of MIL-S-901D, the Navy will shoulder responsibility for the higher levels certain to be encountered under hostilities.

High-impact shock testing, as specified in MIL-S-901D, meets the criterion stated in reference 6 in that the shock tests disclose the same types of equipment shortcomings as are seen in field shock trials. For that reason, MIL-S-901D has endured since World War II with minimal change. The Navy Shock Trials program is used to not only maintain a check on the viability of MIL-S-901D but also to check on the validity of the structural design of ships as regards to shock. There has been a tendency to consider shock trials as equivalent to MIL-S-901D shock tests. However, it should be noted that shock trials seldom reach the shock intensity that may be encountered during combat or even in laboratory tests. Because of the low shock levels, it is not proper to conclude that items of electronic equipment that survived shock trials on a ship are fully acceptable and qualified for Navy shipboard application. Further, elevating the severity of the shock trial's much above what is presently used would bring about an unacceptable risk of injury to or loss of personnel, or even loss of the ship. MIL-S-901D remains the only method of obtaining shock qualification.

Contrary to common belief, MIL-S-901D can be tailored to provide shock sufficiency appropriate to the criticality and location of the equipment on a ship. Paragraph 3.1.6 (a) of MIL-S-901D requires that "... principal units shall be mounted for testing in a manner which dynamically simulates the most severe (normally, the stiffest) mounting condition likely to be encountered in the actual shipboard installation."

When data concerning shipboard mounting locations are available, observing the dynamic simulation mentioned above will provide a natural tailoring of shock levels and thereby tailored equipment shock sufficiency. Figures 34 and 35 show how shock velocity levels and the shock spectrum typically vary with location on a ship. Obviously, the fixture used to attach electronic equipment to the shock testing machine should provide the same shock variation. Shock data are available, due to the Shock Trials Program pursued by the Navy, that provides information needed for fixture design. Published shock data may not directly mention the stiffness of various shipboard locations, but shock-excited natural frequency of a location is closely related to the stiffness of that location. Many shock waveform data are available in shock trial reports, and vertical frequencies appearing in those data can be used as a stiffness indicator. Frequencies measured in a shock trial are to some extent a function of the mass of equipment in a compartment as well as the local stiffness. Small nonlinearies will cause frequencies to change slightly as shock levels increase. Still, these frequencies are an order-of-magnitude better approximation of proper shock fixturing than is the use of "standard fixtures."

Reference 11 discusses the use of specially designed or "tuned" shock fixtures in improving MIL-S-901 tests. Figure 36, based on reference 11, shows a shock spectrum. It shows how the use of a shock fixture, stiffer than the mounting location, creates a shock test that is both an overtest and an undertest. The item being tested on the stiffer fixture receives larger values of acceleration at high frequencies and does not see as much as it should (or as much as it would on the ship) at lower frequencies. Design and application of shock fixtures tuned to shock trial-measured vertical frequencies tailors the MIL-S-901 shock test much more closely to actual needs of the item and its mounting location. Further, as long as the energy input of the test is not changed (hammer height as specified), the intent and requirements of MIL-S-901 have been met.

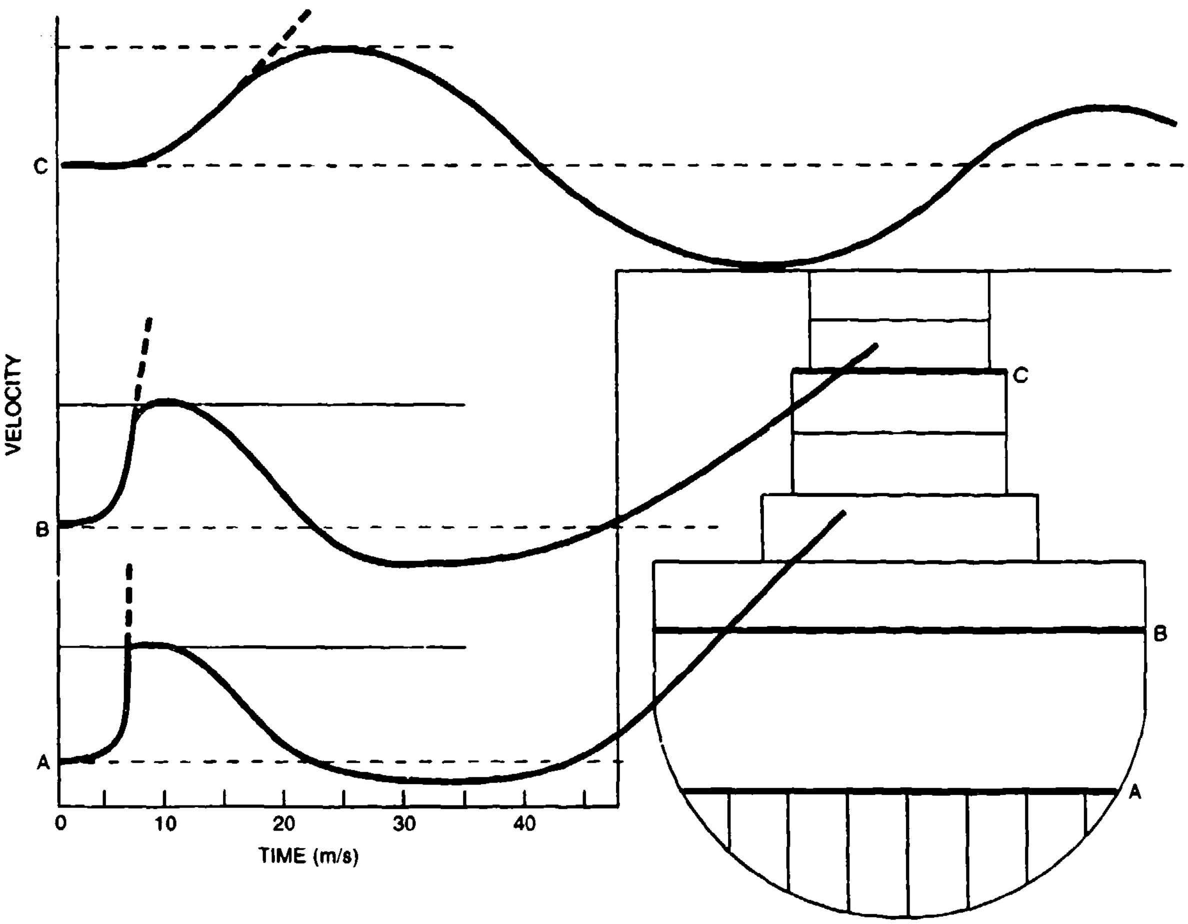

Figure 34. Velocity amplitudes versus time.

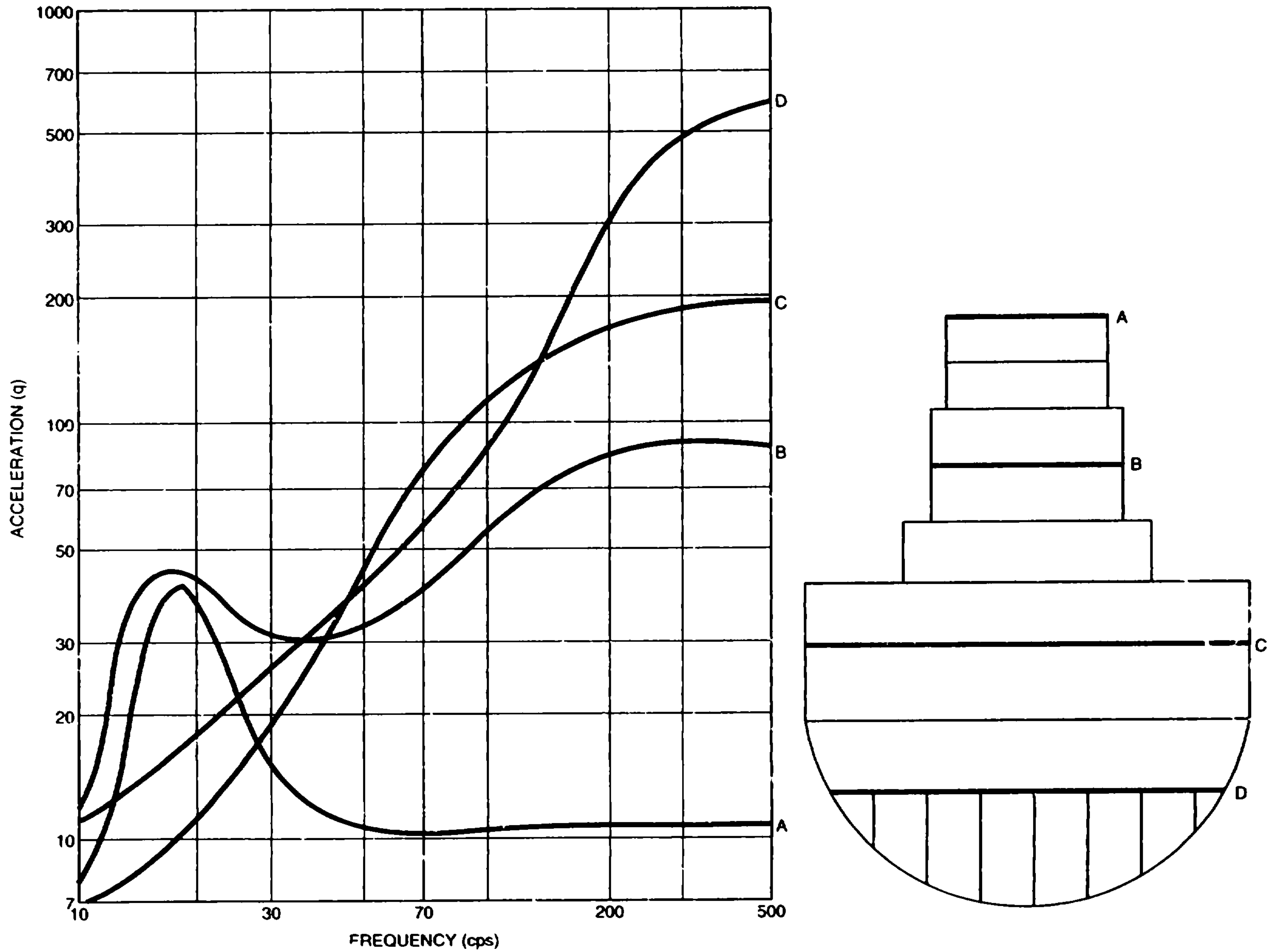

Figure 35. Typical shock spectra.

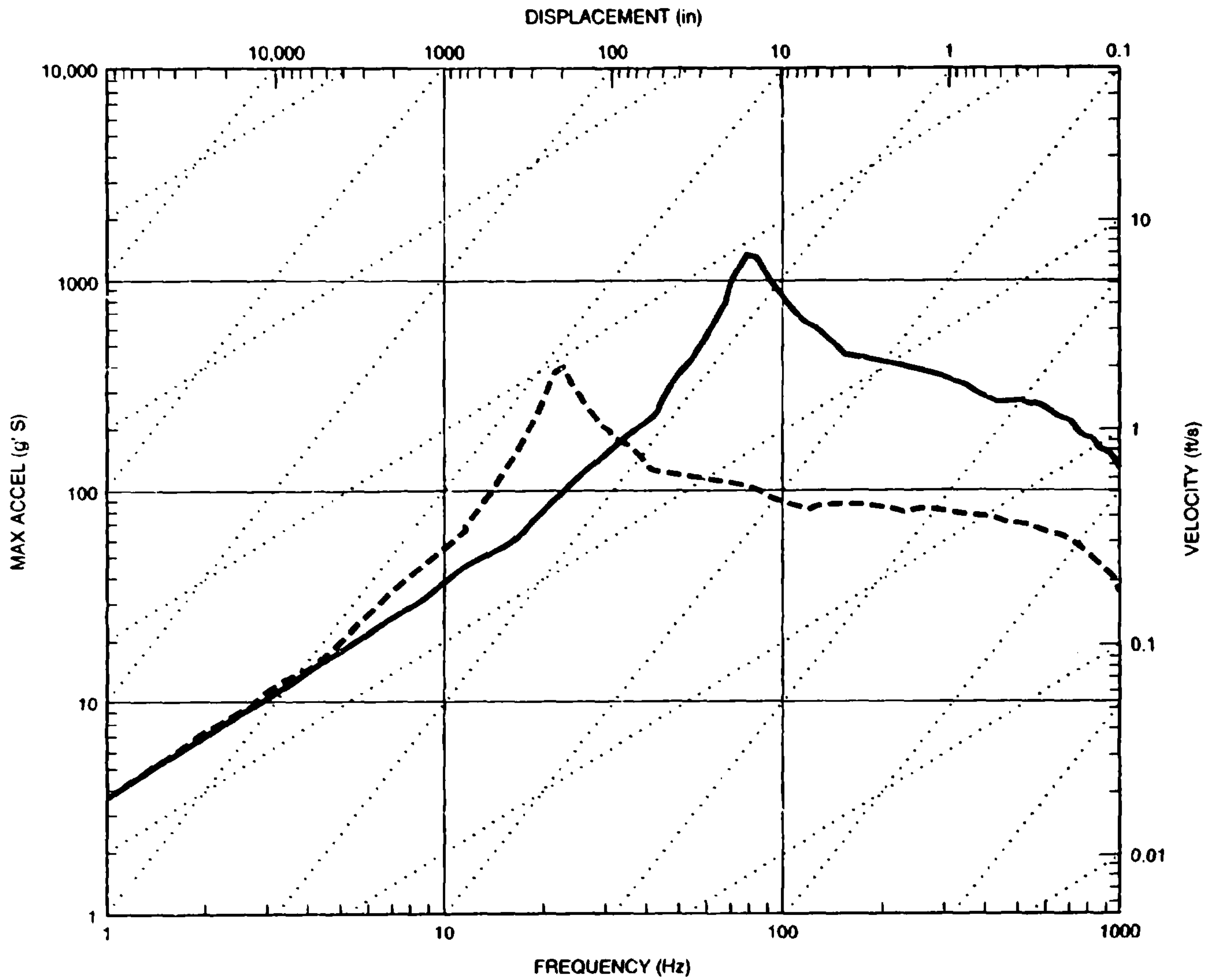

Figure 36. Shock spectrum.

DISCUSSION AND CONCLUSIONS

Information provided in this report allows selection of off-the-shelf equipment that is capable of serving on board Navy surface ships. Where the equipment falls short of what is required, techniques, algorithms, and data are supplied that will allow minimal modification in order to meet ship environment and equipment criticality needs. A suggested approach follows:

a. Determine the worst-case installation location with regard to vibration. Generally, that is a location having the shortest vector distance to the stern of the ships on which the equipment is to be installed. Consider the criticality of the application and calculate the single-frequency vibration amplitude to be used in the procurement specifications.

b. Review temperature and humidity data provided in this report, decide the criticality of the application, and select appropriate temperature and humidity ranges for the procurement specifications.

c. Review shock trials data to determine typical vertical natural frequencies of intended installation locations. Specify that the equipment is to meet the MIL-S-901D shock test while mounted on a fixture providing the lowest natural frequency. NOTE: If natural frequencies of possible mountings differ by more than 25 percent of the lower frequency, use two or more shock fixtures.

d. Ensure that procurement specifications insist that the equipment's ability to meet all environmental requirements be demonstrated by test.

Use of the approach summarized above will result in equipment tailored more closely to actual environmental needs than is the case in the usual "MIL-SPEC" method. Be aware, though, that equipment procured under an environmentally tailored approach cannot be relocated on a ship or installed in new classes without serious reconsideration. To prevent misapplication, a detailed environmental requirements and testing report will have to accompany each item of tailored equipment. There may well be several different levels of tailoring for an equipment and modifications appropriate for the different levels may not be apparent to casual observers. The costs of such confusion in the supply system, or the possibility of serious error, may completely outweigh any savings derived from the tailoring approach. Thus, the "one item, any location" aspect of the "MIL-SPEC" approach has many advantages.

But certain types of electronic equipment can benefit from environmental tailoring due to the criticality or nature of their application. The material covered here is directed to those types of equipment. The user of these tailoring approaches is urged to always consider being a little conservative in reducing environmental requirements. Often, a slightly elevated requirement will greatly enhance possible applications with little increase in development costs.

REFERENCES

1. Harris, C.M. 1988. *Shock and Vibration Handbook, 3rd ed.* pp. 44–41 through 44–43, McGraw-Hill, New York, NY.

2. Naval Ship Engineering Center, Military Standard, MIL-STD-167-1. 1 May 1974. *Mechanical Vibrations of Shipboard Equipment.*

3. Chalmers, R. H. and D. L. Peterson. "Environmental Studies Aboard U.S. Navy Vessels in the South China and the Caribbean Seas," 1986. NELC Report 1577, Aug. AD No. 843890, Naval Electronics Laboratory Center, San Diego, CA.

4. Peterson, D. L. "Summary of NELC-Recorded Shipboard Vibration Data." 1970. NELC Technical Report 1701, (April). Naval Electronics Laboratory Center, San Diego, CA.

5. Leffler, R. "Telecommunications Equipment Low-Cost Acquisition Method (TELCAM)." 1974. NELC Technical Document 335, (July), AD No. A001713. Naval Electronics Laboratory Center, San Diego, CA.

6. Fackler, W.C. 1972. *Equivalence Techniques for Vibration Testing*. Shock and Vibration Information Center. Washington, DC.

7. Chalmers, R. H. "Environmental Profiles for Reliability Testing," NOSC TR 558, 15 June 1980, AD No. B051425. Naval Ocean Systems Center, San Diego, CA.

8. Crandall, S.H. 1959. *Random Vibration*, pp. 43–46, Technology Press of the Massachusetts Institute of Technology, Cambridge, MA.

9. MIL-STD-210C. 9 January 1989. *Climatic Information to Determine Design and Test Requirements for Military Systems and Equipment.*

10. Naval Ship Engineering Center, Military Specification, MIL-S-901D. 17 March 1989. *Shock Tests, H.I. (High-Impact); Shipboard Machinery, Equipment and Systems, Requirements For.*

11. Chalmers, R.H. and R.C. Shaw. 1988. "Using Tuned Fixtures to Tailor MIL-S-901C." *Proceedings of the 59th Shock and Vibration Symposium*. vol. V, pp. 129–162.

APPENDIX A

SHIPBOARD VIBRATIONS FOR RUGGEDIZED EQUIPMENT

SCOPE. All non-mission-critical electronic equipment intended for shipboard use shall demonstrate the capability to perform satisfactorily under the vibration tests described herein. Magnitudes of input motions and associated frequencies are chosen to represent usual conditions aboard ship and do not cover the vibration environment that may exist when a ship has sustained damage and must continue to operate. Users of this test are therefore encouraged to be critical in judging acceptability of the equipment under test.

BASIS OF ACCEPTABILITY. Acceptability is contingent upon the ability of the equipment to perform its function during and after the tests specified in VIBRATION TESTS below. Minor damage or distortion will be permitted during the test providing such damage or distortion does not in any way impair the ability of the equipment to perform its principal functions or promise to shorten its service life. Because of the numerous types of equipment covered by this document, a definite demarcation between major and minor failures cannot be specified. Therefore, such decisions must necessarily be left to the judgment of the test engineer.

In general, a major failure is one which would cause malfunction of the equipment for a long period, or behavior which suggests early equipment failure in the field. Nonrepetitive failures that can be repaired or reset quickly and easily are generally considered minor. As such, a repair could be made and the test continued without penalty. Sometimes, the shipboard application of the equipment will determine the category of the failure; for example, a momentary loss of memory in a computer used in tracking spare parts may be considered minor, while the same failure in a fire control computer would be major. Thus, it is the test engineer, command, or agency concerned that shall be responsible for judging major or minor failures.

INTENT OF TESTS. Vibration tests specified herein are intended to assess how well an item might withstand exposure to usual levels of surface ship vibration. This is done by identifying frequencies at which the equipment under consideration exhibits amplified response and imposing a 2-hour endurance test at those frequencies. Further, 2-hour exposures to random vibrations indicate if the item under test is likely to respond unfavorably due to multifrequency excitation during its service life.

TESTING MACHINES. Any vibration testing machine capable of providing the specified motions to the attachment points of the equipment under test may be used. Means shall be provided for controlling the direction of vibration and for keeping the frequencies and amplitudes within prescribed limits. If the lower frequency limit of 4 Hz cannot be reached, any available machine may be used upon the approval of the command or agency concerned. This applies, also, if natural frequencies of the equipment under test in translation and rocking modes do not lie below the lowest frequency of the testing machine. In no case shall a testing machine be used that has a minimum frequency greater than 10 Hz.

METHODS OF ATTACHMENT. For all vibration tests, the equipment shall be secured to the vibration machine in the same manner in which it will be secured in its shipboard mounting. If alternative mountings of the equipment are possible, complete vibration tests shall be conducted in each alternative mounting configuration.

FIXTURES. Fixtures used in attaching equipment to the vibration machine shall be sufficiently rigid to ensure that motion at all points of attachment of the equipment is essentially the same as the main machine platform. For large items that require overhead or bulkhead support, or when appreciable interaction with ships structure is probable, the attaching fixture should be designed to approximate the mechanical impedance of the ships structure as seen at the equipment mounting points. When this fixturing approach is used, complete documentation of the installation site assessment, fixture design, and fixture testing shall be included in the test report. Also, the documentation of command or agency approval of the fixture and its use (see TEST REPORT below) shall be included.

PORTABLE EQUIPMENT. Equipment not intended for permanent attachment on a ship shall be attached to the testing machine in a manner representative of that in which it will be stored on the ship. In many cases, this will mean the item will be secured to the vibration machine by small woven straps or a line.

ORIENTATION FOR VIBRATION TESTING. Equipment shall be installed on vibration testing machines in such a manner that the direction of vibration will be, in turn, along each of three orthogonal axes of the equipment as installed on the ship, that is, vertical, athwartship, and fore and aft. On a horizontal vibration testing machine, the equipment can be rotated 90 degrees about a vertical axis in order to vibrate it in each of the two horizontal orientations. At no time shall the equipment be installed in any other than its normal orientation (on its side or upside down, for example). Because no particular orientation of portable equipment can be considered normal, orientation of portable equipment for vibration testing shall be left to the discretion of the test engineer.

RESILIENT MOUNTINGS. Equipment, which is to be installed on resilient mounts on board ship, shall be installed on those mounts for vibration testing. Resilient mounts integral to the equipment (intended to protect sensitive devices within the equipment) shall be left in place and operational

VIBRATION TESTS

Each of the tests specified herein shall be conducted separately in each of three principal axes. All sinusoidal tests in one axis (Exploratory, Variable Frequency, and Endurance) shall be completed before proceeding to the next axis. Random Tests in that axis can also be performed providing the Random Test configuration is essentially that of the sinusoidal tests.

During the tests, the equipment shall be secured to the test machine and oriented as specified in METHODS OF ATTACHMENT, FIXTURES, and RESILIENT MOUNTINGS above. The equipment shall be energized and performing its normal functions or nonenergized if, in the opinion of the test engineer, the equipment is more susceptible to vibration damage in that condition. Appropriate test and peripheral equipment shall be applied to the equipment under test to reveal vibration-caused electrical malfunctions that are not manifested in mechanical responses. Unless otherwise directed, the test shall be discontinued if a major failure occurs, and the entire vibration test series repeated following repair or correction of deficiencies. An entirely new test specimen may be substituted for the retest, but the substitution shall be noted in the test report (see TEST REPORT below). The amplitude of a single-frequency vibration shall be as follows:

for surface ships except carriers

$$Vp = \frac{1.7}{(D - 30)^{1/2}} \qquad \text{(A-1)}$$

where Vp is peak acceleration at any frequency 4 - 50 Hz, G,

D is distance from stern to installation location, feet;
for carriers

$$Vp = \frac{1.5}{(D - 30)^{1/3}} \qquad \text{(A-2)}$$

Spectrum values for random vibration shall be as follows:

for Category I type ships (PG, PGH, PHM)
(0.58 G rms)

0.01152 G**2/Hz	at 4 Hz
0.00662 "	at 30 "
0.00144 "	at 53 "
0.00029 "	at 65 "
0.00029 "	at 200 "

for Category II type ships (CV, CVN)
(0.49 G rms)

0.00048	G**2/Hz	at 4 Hz
0.00352	"	at 60 "
0.00088	"	at 75 "
0.00053	"	at 200 "

for Category III type ships (DE, DD, DDG, FF, CG, FF 963)
(0.60 G rms)

0.00621	G**2/Hz	at 4 Hz
0.00539	"	at 60 "
0.00083	"	at 70 "
0.00083	"	at 200 "

for Category IV type ships (LCC, LHA, LSD, LPA, LKA, LST)

use parameters from Category V

for Category V type ships (unlisted types, or more than one of the above groupings)

(0.74 G rms)

0.01152	G**2/Hz	at 4 Hz.
0.00539	"	at 60 "
0.00088	"	at 75 "
0.00083	"	at 200 "

a. *Exploratory Test*. Exploratory Test input amplitude in all three directions shall be that calculated from the above single-frequency equations, with D chosen to suit the installation site closest to the screws. Displacement may be limited to no more than 0.1 inch peak to peak. Vibration input shall be swept linearly (equal time at each frequency) from 4 to 50 Hz in no less than 23.5 minutes, nor more than 47 minutes. NOTE: The Exploratory Test is intended to reveal major vibration sensitivities so that corrective action may be taken before severe damage is incurred. If the test engineer feels the item under test is under no threat, the Exploratory Test may be skipped.

b. *Variable Frequency Tests*. Variable Frequency Test input amplitudes in all three directions shall be twice that calculated from the above single-frequency equations, with D chosen to suit the installation site closest to the screws. Displacement may be limited to no more than 0.1 inch peak to peak. Vibration input shall be swept linearly from 4 to 50 Hz in no less than 235 minutes. Significant amplifications of motion by the item under test shall be noted, as shall be any change in the item's electrical performance.

c. *Endurance Tests*. Endurance Test input amplitude in all three directions shall be twice that calculated from single-frequency equations A-1 and A-2 above, with D chosen to suit the installation site closest to the screws. Displacement may be limited to no more than 0.1 inch peak to peak. Vibration shall be input at each peak response frequency noted in the Variable Frequency Test for 2 hours. In the event no peak responses were noted during the Variable Frequency Test, a 2-hour dwell at 50 Hz shall be applied. During the 2-hour dwell, input frequency shall be varied as is necessary to keep response of the item under test peaked (heating and wear generally lower peak response frequencies). Magnitude of the change of peak response frequency and final motion magnification shall be noted.

d. *Random Vibration Test*. Random vibration, with spectral density as appropriate for the ship type, shall be applied for 2 hours in each of three orthogonal axes. In the case of large equipment with complex, multiplaned fixtures, vibration may be applied at one attachment point or more at a time, until all are covered, with the time of exposure kept at 2 hours in each of three orthogonal axes at each attachment point.

TEST REPORTING. The Test Report to be furnished to the applicable command or agency by the testing laboratory shall include a physical description of the item being tested. As a minimum, information supplied shall include dimensions, weight, center of gravity, how the item was attached to the testing machine, and photographs of the testing setup. The report shall list all peak response frequencies and their approximate amplification factors. Detailed descriptions or photographs of any damage or malfunctioning incurred shall be included along with any indications of impending degradation or failure and at what stage of testing it was noted. Recommendations for corrective measures are desired.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
April 1991

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE
TAILORING SHIPBOARD ENVIRONMENTAL SPECIFICATIONS
A Guide for Navy Program Managers

5. FUNDING NUMBERS
PE: 0602234N
AN: DN306 243

6. AUTHOR(S)
R. H. Chalmers

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Ocean Systems Center
San Diego, CA 92152–5000

8. PERFORMING ORGANIZATION REPORT NUMBER
NOSC TD 2071

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Technology
800 North Quincy Street
Arlington, VA 22217

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This document describes shipboard environmental conditions and environmental requirements to guide computer system acquisition managers in tailoring environmental specifications effectively in their procurement documents. Environmental conditions considered in this document include natural and induced levels of vibration, temperature, humidity, and shock. The environmental levels described are based on location of the installation site on the ship and on the degree of mission criticality associated with the equipment being procured. The philosophy and empirical data underlying the environmental levels required by military specifications are discussed, allowing acquisition managers to select lower environmental levels should they choose to assume the additional risk. Tailored testing methods and mechanical design approaches and trade-offs for modifying fragile equipment to protect it from harsh environments are also addressed.

14. SUBJECT TERMS
shipboard environmental specifications

15. NUMBER OF PAGES
69

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAME AS REPORT

21a. NAME OF RESPONSIBLE INDIVIDUAL	21b. TELEPHONE (Include Area Code)	21c. OFFICE SYMBOL
M. L. Crowley	(619) 553-3535	Code 41

INITIAL DISTRIBUTION

Code 0012	Patent Counsel	(1)
Code 401	R. A. Wasilausky	(1)
Code 41	M. L. Crowley	(30)
Code 41	A. G. Justice	(1)
Code 412	L. J. Core	(1)
Code 412	P. N. Pham	(1)
Code 412	D. F. Romig	(1)
Code 412	D. G. Sheriff	(1)
Code 412	V. D. Tran	(1)
Code 412	D. R. Wilcox	(1)
Code 413	L. C. Anderson	(1)
Code 423	S. Brenneman	(1)
Code 4306	R. J. Jaffee	(1)
Code 6201	R. Eyres	(1)
Code 821	F. Duffy	(1)
Code 821	E. A. Howard	(1)
Code 90	I. E. Lemaire	(1)
Code 93	C. L. Ward, Jr.	(1)
Code 95	R. E. Miller	(10)
Code 9502	R. H. Chalmers	(10)
Code 951	T. A. Danielson	(1)
Code 951	R. K. Fergin	(1)
Code 951	J. L. Walker	(1)
Code 951	W. R. Webster	(1)
Code 952	J. Puleo	(1)
Code 961	Archive/Stock	(6)
Code 964B	Library	(3)

Defense Technical Information Center
Alexandria, VA 22304-6145 (4)

Center for Naval Analyses
Alexandria, VA 22302-0268

Space & Naval Warfare Systems Command
Washington, DC 20363-5100 (5)

Naval Surface Warfare Center
Silver Spring, MD 20903-5000

Naval Sea Systems Command
Washington, DC 20362-5101 (2)

Naval Weapons Support Center
Crane, IN 47522-5060 (2)

Naval Underwater Systems Center
New London, CT 06320-5594

NOSC Liaison Office
Washington, DC 20363-5100

Office of Naval Technology
Arlington, VA 22217-5000 (10)

Naval Air Development Center
Warminster, PA 18974-5000 (3)

Naval Surface Warfare Center
Dahlgren, VA 22448-5000 (2)

Naval Underwater Systems Center
Newport, RI 02841-5047

Naval Surface Warfare Center
Silver Spring, MD 20903-5000 (2)

END

FILMED

DATE: 8-91

DTIC